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Crater Lake

Gem of the Cascades

The Geological Story of
Crater Lake National Park

2nd Edition

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TO

THE EARLY EXPLORERS AND SETTLERS OF THE HIGH CASCADES, ESPECIALLY THOSE WHOSE DAILY CHORES FAILED TO SMOTHER THEIR APPRECIATION AND ENJOYMENT OF PLACES LIKE CRATER LAKE. BECAUSE OF THEIR INTEREST AND EFFORTS TO PRESERVE CLASSIC NATURAL AREAS, THESE AREAS ARE NOW AVAILABLE FOR ALL TO VISIT. AND TODAY, I AM ABLE TO STUDY GEOLOGY IN AN ORIGINAL AND UNDIMINISHED STATE.

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Preface

Crater Lake certainly is a gem; one of the crown jewels of the United States which we call National Parks. Indeed, no other country has such a national heritage of natural areas. Crater Lake occupies a special place in the memories of anyone who has ever visited and learned its geological story. It also occupies a special place in classic geological thought and theory. Any geologist can tell you why. To a major degree, Crater Lake's fame results from its geological past and the ability to interpret that record today. That's what this book is about.

My intention in writing and producing this little volume on the geology of Crater Lake National Park stems, from a desire to explain this wonderful bit of landscape to park visitors and others interested in the park. Although it's meant for the layman, trained geologists may find some of the ideas refreshing. In planning and actually carrying out the myriad details required to prepare even a small book, I have attempted to keep both audiences in mind. The results of this effort can be found in the abundance of photographs, diagrams, maps and tables, to display Crater Lake's geology in a graphical manner. These are, of course, familiar to geologists but also helpful, I trust, to every reader.

Although interest in the geology of Crater Lake has increased in recent years, especially since Mount St. Helens started erupting in 1980, much of the scientific literature is older. Many of the concepts in this book, applying to the geology of the park, have been taken from studies of other areas. For those with a continuing interest in volcanology and calderas, I've included a reference list in the appendix. Another appendix aide is the index keyed to the more technical terms required to convey the concepts used.

Many friends and colleagues have assisted in this adventure. A special word of appreciation goes to Dr. Charles Bacon, with the United States Geological Survey, for his unlimited patience in responding to my unending questions and for his extra effort to include me in numerous field activities. Thanks go to my wife Sharon for typing assistance, Betty Hansen for a thorough reading of the entire manuscript, and Larry Smith for his critical review of the first chapter. The necessary field study provisions were made possible by Mark Forbes, Ron Warfield, Hank Tanski, and Pat Smith of the Crater Lake National Park Service Staff. Thanks to everyone !

K.R. Cranson
Lansing, Michigan
May 1, 1982

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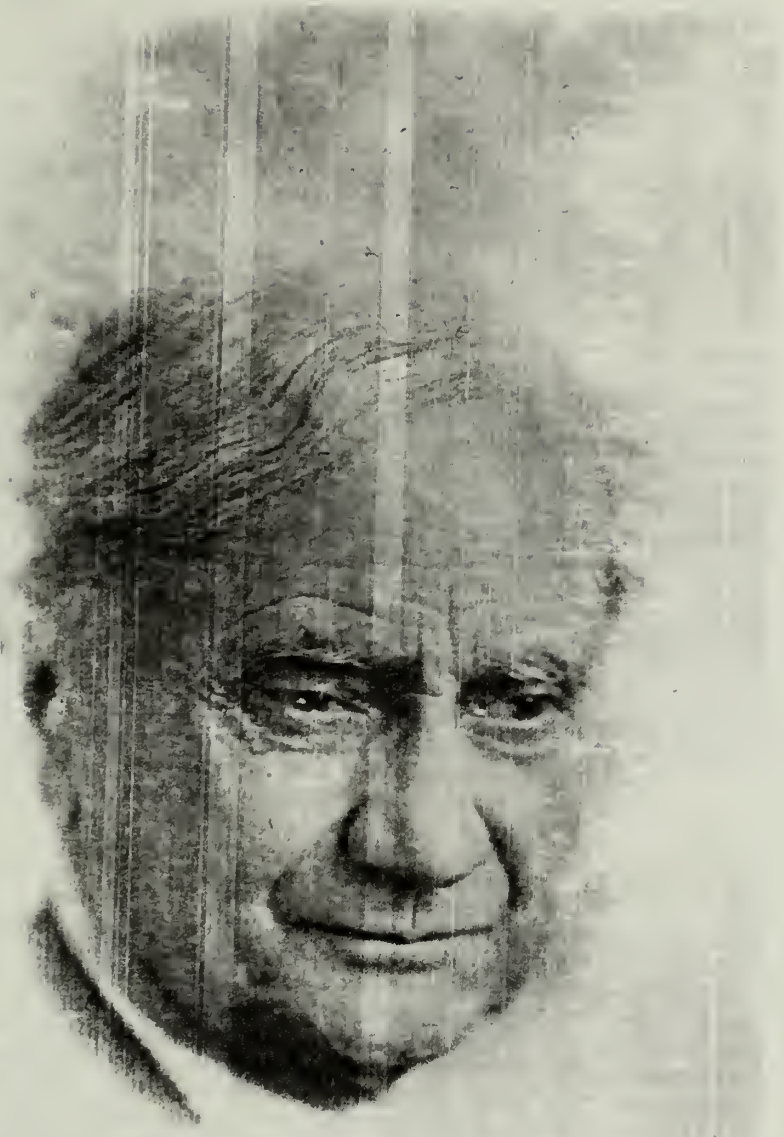
Chapter 1

Discovery

Late in the afternoon on June 12, 1853, a small band of gold prospectors rode slowly up a mountain draw in south central Oregon. They were in search of the legendary Lost Cabin Gold Mine and the instant fortune that it would surely provide. Although details are sketchy, it appears that three members of this party, John Hillman, Isaac Skeeters and Henry Klippel, were ahead of the others and unaware of what existed just beyond the ridge. Little did they realize what the next few hours had in store for them, and ultimately, the entire United States.

These men had arrived in Jacksonville, Oregon, the previous fall. They had come for the new gold "diggins" discovered in the local streams. The winter of 1852-53 was especially severe with early snows and a scarcity of provisions for livestock as well as the people of this small mining camp. Spring had brought new hope and the prospect of riches in the gold fields around Jacksonville.

As preparations were being made to head out to the gold fields, eleven miners from California arrived in



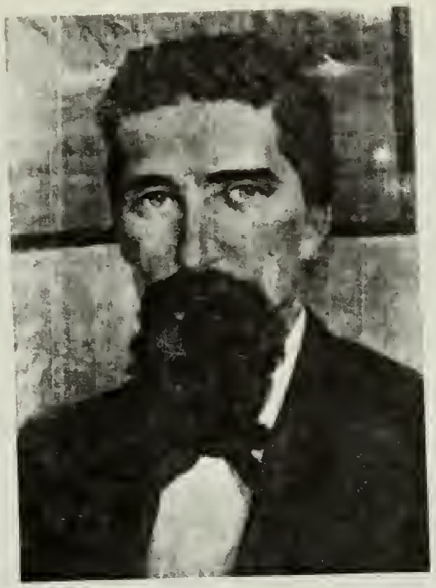
1-1 WILLIAM GLADSTONE STEEL Steel's first visit to Crater Lake spawned the national park idea for the region. This thought was shared with Dutton who suggested having President Cleveland reserve ten townships for a public park. Steel is responsible for naming many of the features in the park as well as much of the early scientific work.

town and purchased large amounts of supplies. Although they were secretive about their mission, one Californian became quite talkative and told how their leader knew of certain landmarks which would surely lead them to the Lost Cabin Mine. This discussion was of great interest to some of the locals and when the Californians left town the next day, eleven Oregonians were on their trail. A game of "hide and seek" developed between the two groups until provisions began to run low. Then for a few days, they searched for the mine and hunted game together. The lack of food caused most of the men to return to Jacksonville but seven continued the search.

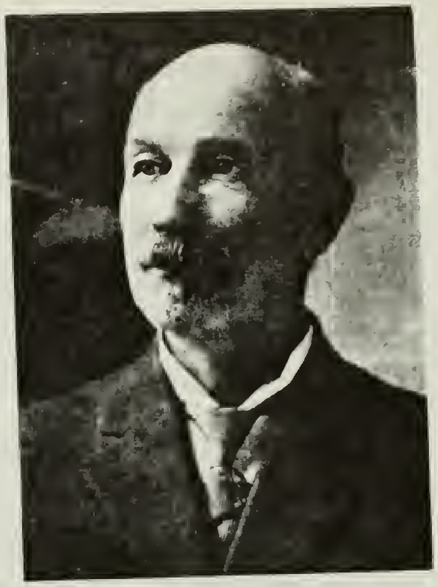
Upon reaching the crest of the ridge, the three miners encounterd a deep basin containing the most beautiful lake any of them had ever seen. Cliffs towering over a thousand feet high surrounded the deep, blue water of this mysterious lake that stretched out before them. Hillman was led to call it the bluest lake he had ever seen and the others made similar comments. After considerable discussion, including a vote, they commemorated the discovery by writing "Deep Blue Lake" on a page torn from the back of a memorandum book which one of the Californians carried. This was placed on a stick near Discovery Point along the rim just west of Rim Village. Upon returning to Jacksonville, their discovery was confirmed, for no one knew anything about the lake that the party of prospectors had found. Since gold was more important than deep blue lakes, the discovery was quickly forgotten.

Early Visitors

Although it's not known if any of this original group ever returned to the site, other early residents did visit the lake. Nearly ten years later, on October 21, 1862, a party of mule packers and gold miners led by Chauncy Nye, happened onto the lake while returning to Jacksonville from the John Day country in eastern Oregon. Their brief description and location of "Blue Lake", as they had named it, appeared in Jacksonville's Oregon Sentinel and became the first published report. In early August of 1865, two soldiers from Fort Klamath stumbled upon Crater Lake while hunting game. Later, they returned accompanied by Captain E.B. Sprague and several curious civilians to make the first descent down to the water. Again, an account was published of their discovery of "Lake Majesty" by the Oregon Sentinel in September of that same year.



1-2 JOHN WESLEY HILLMAN
Hillman (only 21 at the time) is often given credit for the discovery of Crater Lake. The location of Discovery Point is based on a discription by Hillman in response to a request from Steel.



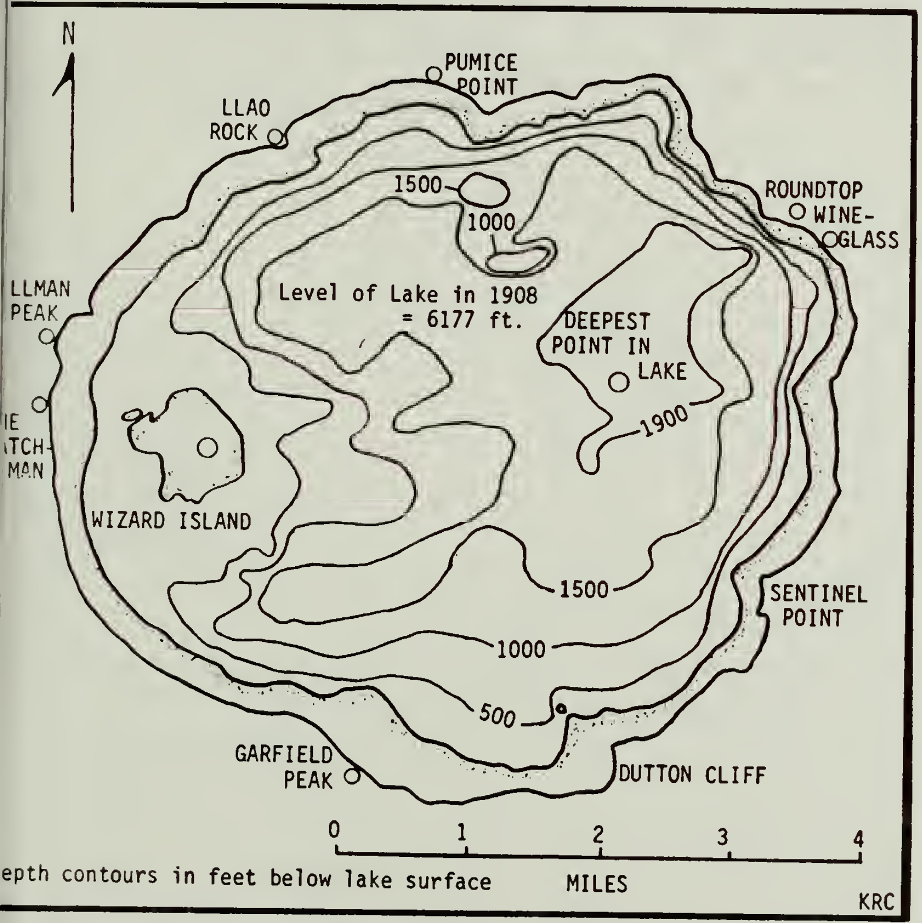
1-3 JOSEPH S. DILLER
Diller and Patton's studies in the area during the 1890's resulted in the first major scientific explanation and publication on the origin of Crater Lake. Their interpretation and collapse theory has proven to be basically correct.

Visits became more frequent as Jacksonville residents and Fort Klamath military personnel made trips to this most unusual place. Among these early visitors to Crater Lake was Jim Sutton, Editor of a Jacksonville newspaper. After some investigations and consideration of how the lake was formed, he suggested that it occupied the crater of an extinct volcano. With this in mind, Sutton wrote an account of one visit in which he referred to "Crater Lake", and thus the name came into common use.

Although the Hillman party has claim to the discovery of Crater Lake, they were certainly not the first to know of its existence. Evidence is clear that the Native Americans who resided in the region were familiar with this place. No less than four legends

efer to Crater Lake and/or its origin.

The Klamath Indians revered Crater Lake as the
ome of Lao, a powerful spirit and chief over many of
e lesser spirits. Because of their belief that pun-
shment would visit those who looked upon places sacred
spirits, few had ever been to Crater Lake. This may
so explain why the early settlers had not learned of
e lake from the Native Americans. Although Hillman
cated Indians that knew about Crater Lake, they re-
sed to discuss any details.



1-4 CRATER LAKE'S FLOOR Prior to 1957, the configuration of Crater Lake's floor was primarily based on the 168 soundings of the Dutton Survey in 1886. Park naturalists also made some depth measurements which are included on this map. (after Williams, 1942)

The person most intimately associated with Crater Lake was William G. Steel. Upon seeing the lake for the first time in August of 1885, Steel was so impressed with its beautiful wild state that he "came under conviction" to save this "wonderful spot." Over the ensuing seventeen years, his writings, lectures, and personal finances were dedicated to this cause. It is quite accurate to say that William Gladstone Steel is the father of Crater Lake National Park, for it was largely through his efforts that Congress created the nation's fifth oldest national park in 1902.

Early Geological Research

In his efforts to gain national attention for Crater Lake, Steel encouraged scientific exploration of this unusual geological feature. Major Clarence Dutton's survey, sponsored by the United States Geological Survey, made the first detailed soundings of the lake during the summer of 1886 and produced a map showing the lake's depth (Map 1-4). A reconnaissance of the geology was also carried out, which clearly established the fact that a large volcanic cone had once stood at the site. Today, only the lower portion of this major volcanic cone remains.

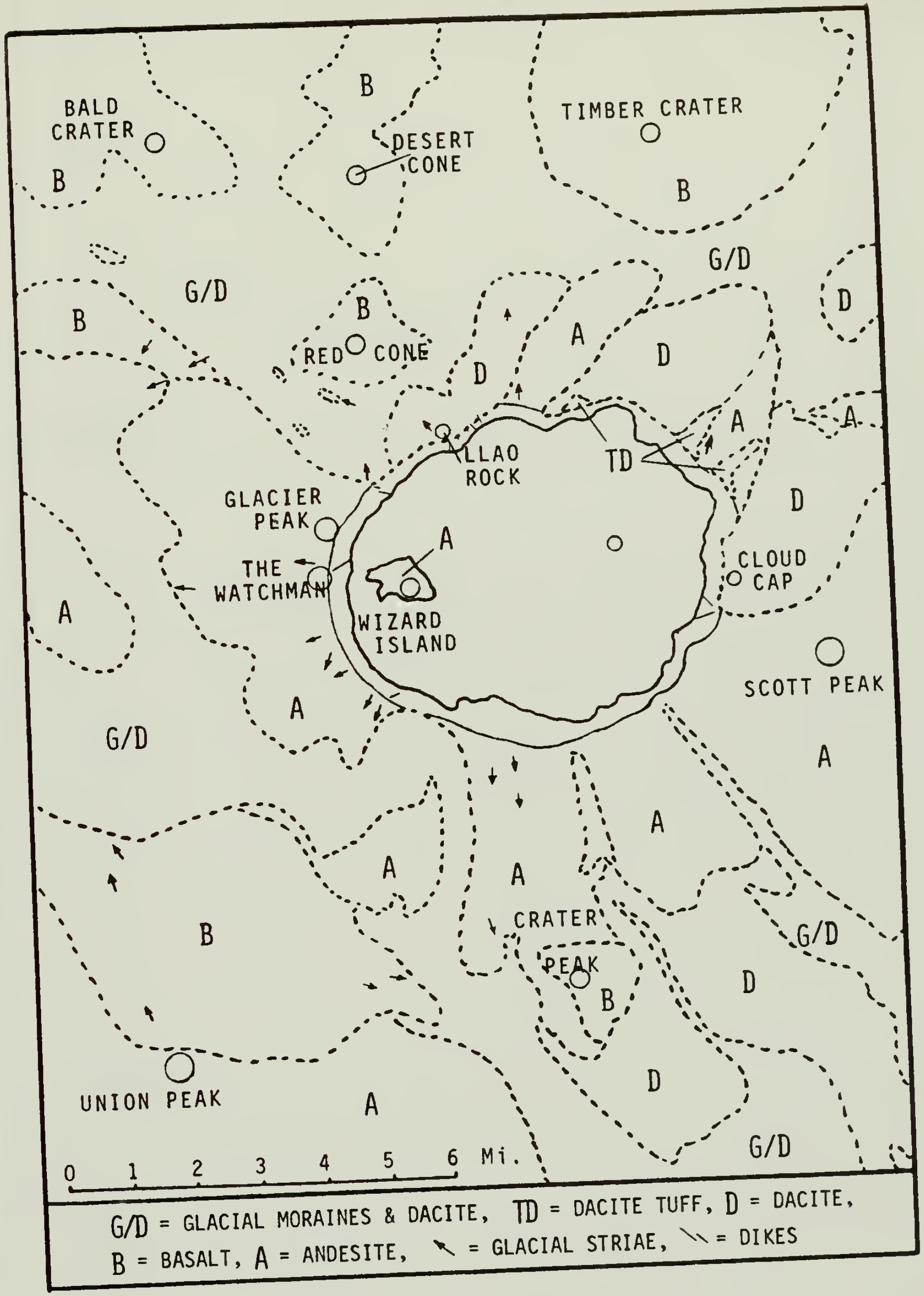
Some twenty years later, a detailed geological study was conducted over several seasons by J.S.Diller and H.B. Patton. Their work included collecting and analyzing rock samples, as well as a detailed study of the surface geology (Map 1-5). With their final report issued in 1902, the first complete geological story of Crater Lake was proposed. After Dutton established the presence of a large volcano, a popular story developed suggesting that a great explosion blew it apart. Diller and Patton's study, however, was even more exciting for they offered a better explanation of what had happened. In their work it became apparent that something caused the upper portion of the cone to collapse into the interior, forming a deep surface depression. When the remains of this volcano filled with water, Crater Lake was born.

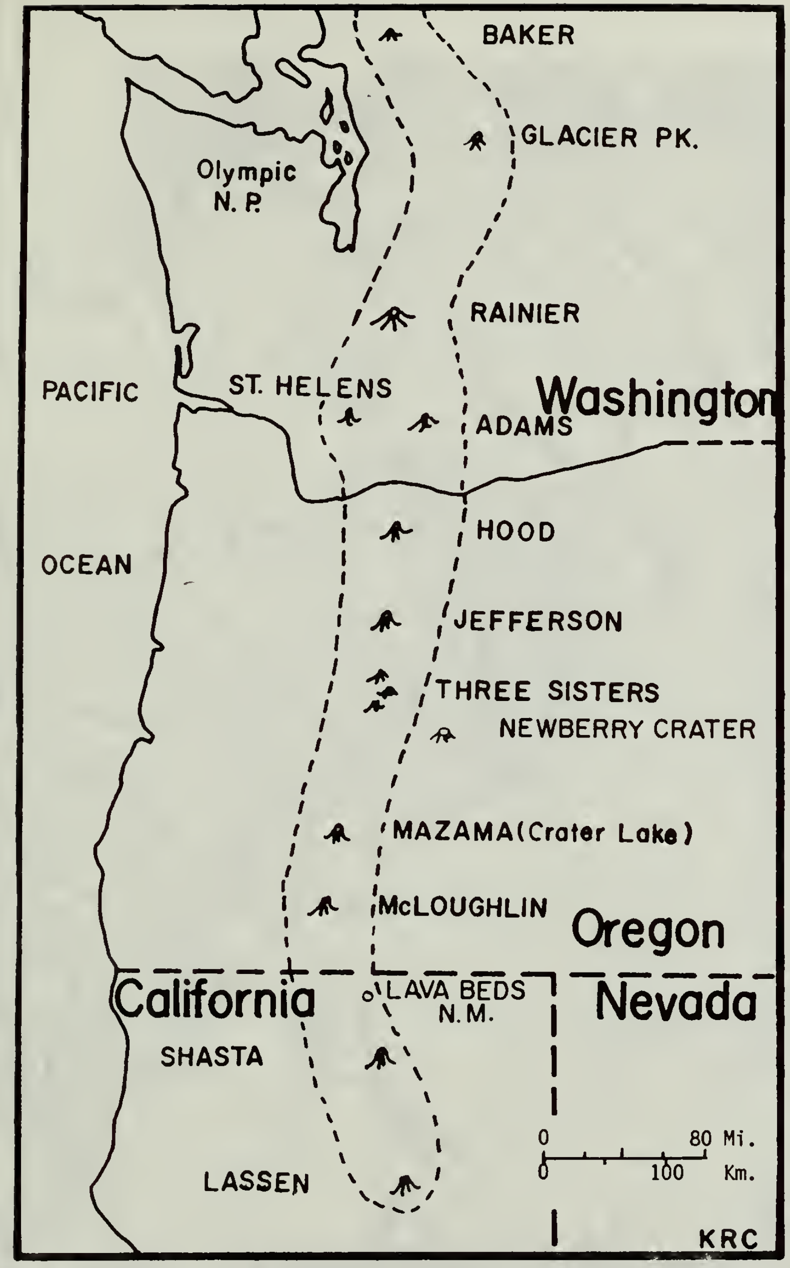
Again, it seems the Native Americans must also be given credit for understanding how Crater Lake formed. Although their explanation is couched in terms of spirits and legends, it is essentially a description of what modern geology has found. This should not come as

a surprise because it's quite likely they were eyewitnesses to the actual event which formed Crater Lake.

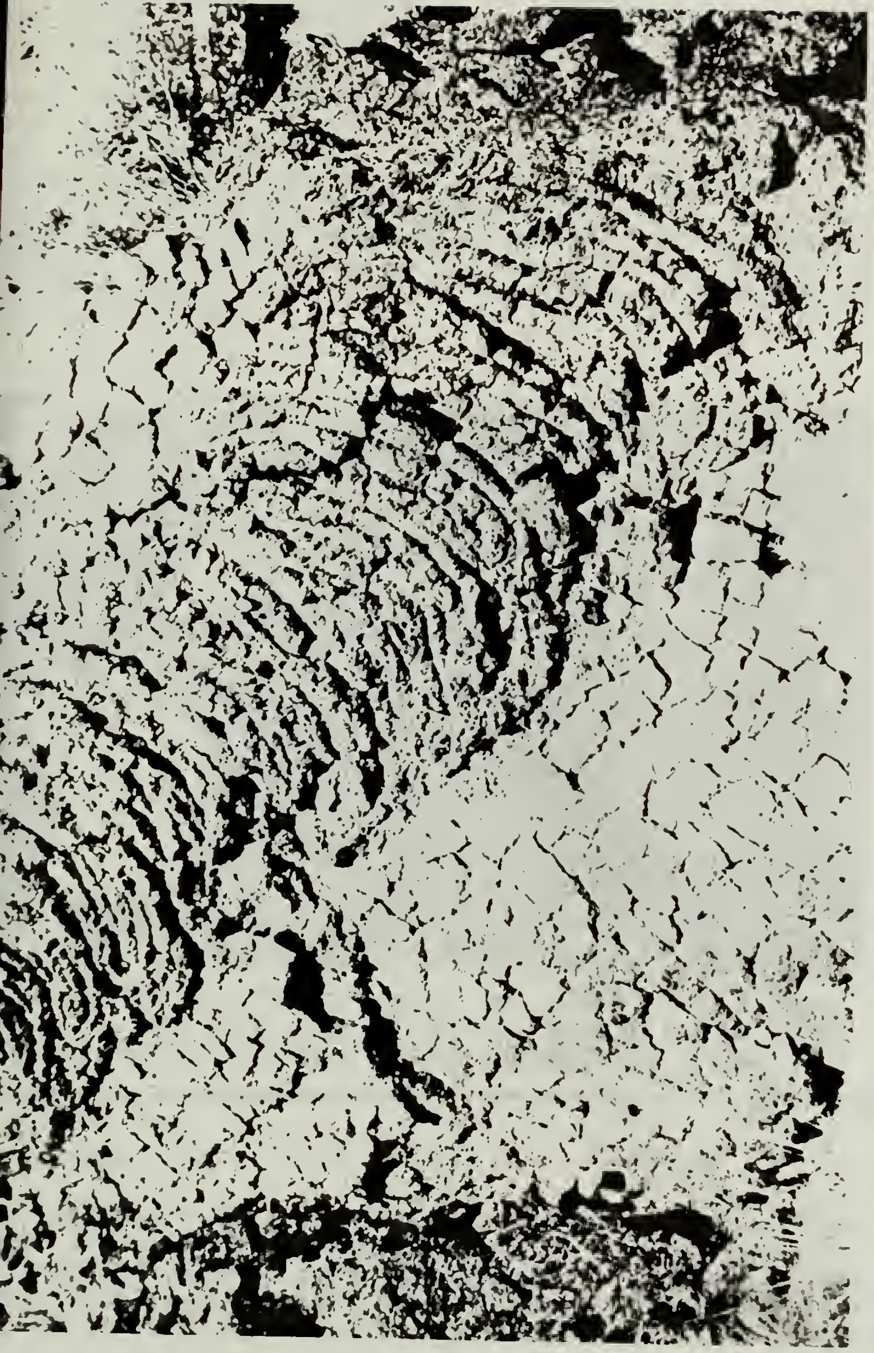
As geological field studies were being carried out in the 1890's, a group of mountain climbers from Portland, known as the Mazamas, held their annual meeting at Crater Lake. This club, organized by Steel in 1894, gathered for their 1896 outing along the southern rim. Also invited were a number of prominent scientists including Dr. Diller. Activities included nature walks and evening campfire lectures describing the natural history of the area. As a part of the official business to be transacted, Steel proposed that the ancestrial volcano be named for the Mazama club. This suggestion was favored and a new name appeared on the map in southern Oregon; Mount Mazama.

1-5 EARLY GEOLOGICAL MAP Diller and Patton produced a colored geological map of Crater Lake National Park for their 1902 Professional Paper. It was printed on a topographic base and included the depth soundings made by the Dutton Survey.





1-6 HIGH CASCADES The location of the major volcanoes which compose the High Cascades are shown here. This mountain chain is the most active volcanic region in the continuous United States.



Chapter 2

Cones, Craters and Calderas

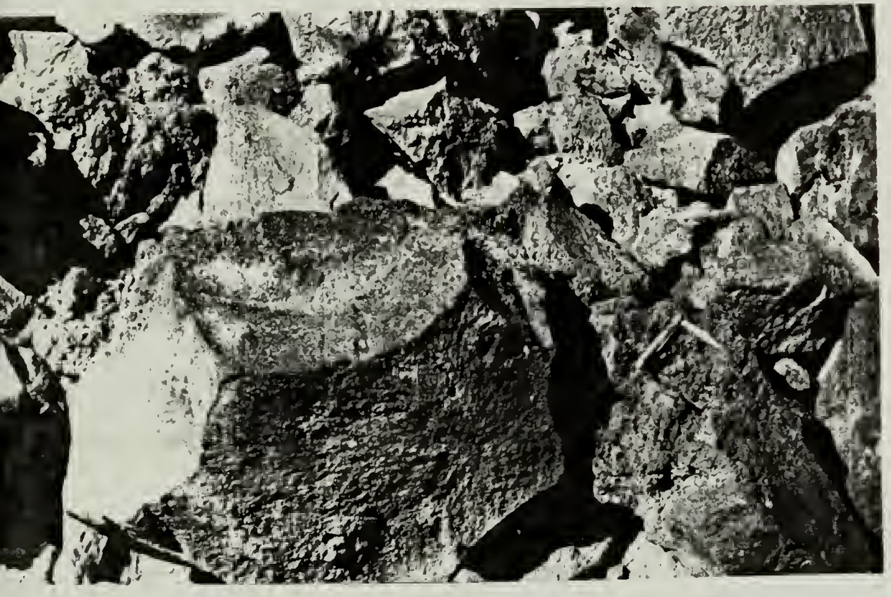
Perhaps the most common image that comes to mind with the term volcanism is red hot lava, flowing down the flanks of an erupting volcano. After all, such pictures are frequently shown to illustrate volcanic activity, usually from some currently erupting vent. There are, however, other materials that are ejected from volcanoes, ranging from hot gases, lava too thick to flow, to solid bombs and blocks. A two-fold classification system has been developed for volcanic rocks. Rock material hot enough to be liquid is called lava while materials ejected as solid particles are pyroclastics ("fire broken" rocks).

Lava

Since lava is hot enough to flow when its temperature is between 1,300°F to 2,100°F (700°C to 1150° C), it must cool before it solidifies into rock. Depending on its temperature at the time of eruption and the cooling conditions encountered, several types of lava may form. Pahoehoe (Pa-hoy-hoy) is the most fluid and

2-1 ROPY PAHOEHOE This form of lava is usually associated with basaltic compositions and is therefore not common in the andesites or dacites found at Crater Lake. This pahoehoe flow occurred at Lava Beds National Monument in northern California.

hile cooling takes place, a crust forms on the surface f the flow. As this partially solidified skin is carried along by the flowing lava below, it may be deform-d or broken. As the flow slows down, the surface piles p to form a ropy-looking mass (Picture 2-1) while apid movement of the underlying lava causes fracturing nto slabs. In cooler flows, the skin is thicker but uch less plastic. Thus, when movement of the more luid underlying lava occurs, this rigid surface breaks nto blocks (Picture 2-2). This blocky lava is often iven the strange name of aa (ah-ah). While actually orming, aa flows appear to be slowly moving piles of linkers which may provide an occasional view of the ot lava inside.



2-2 AA LAVA This form of lava is the common flow surface seen in the park. One of the best examples can be found around the base of Wizard Island (note knife for scale).

Pyroclastics

Pyroclastic ejecta takes on many more forms than fluid lava. This erupted material is usually pieces of solidified volcanic rock but may also be molten clots that cool rapidly to a solid. Geologists use the term tephra to refer to volcanic products that have been shot into the air and have fallen back to earth. The classification of tephra is based on the size of individual particles as listed in Table 1. The smallest category; ash, may be small indeed and is often transported great distances from the place where it erupted (Picture 2-3). With increase in size, ash particles are transported shorter distances with the largest falling out near the site of the eruption. Although lapilli is not as abundant as the ash-size particles, it is still common in volcanic areas (Picture 2-4). The marble-size particles associated with cinder cones and other explosive eruptions fall into this class. Perhaps the most spectacular tephra class is blocks and bombs (Picture 2-5). While blocks are angular shaped fragments, most likely a solid at the time of their ejection, bombs often have a more rounded appearance. Highly streamline shapes suggest that bombs of this type were molten when ejected and achieved their shape while moving through the air.

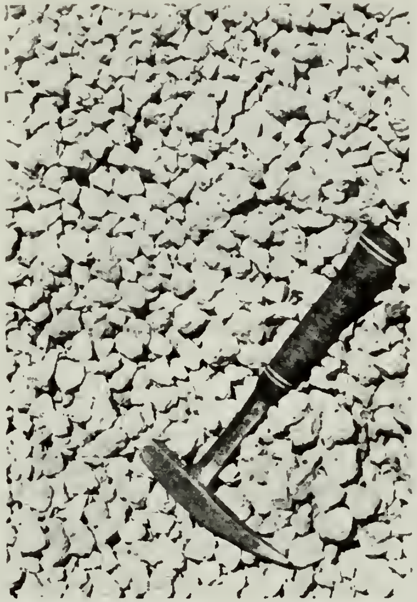
TABLE 1 CLASSIFICATION OF TEPHRA (AIR FALL)

NAME	SIZE	DESCRIPTION
Ash	Less Than 2mm(3/64 in.)	Consists of glassy particles easily transported by wind
Lapilli	2mm to 64 mm*	Often spheroidal in shape but may be elongated. Developed from liquid ejecta or by the accretion of smaller particles. Term means "little stones".
Bombs	Larger Than 64mm (2½ in.)	Clots of magma partly or entirely plastic upon eruption. The shape is the result of initial fluidity, rate of cooling, time in flight and other factors. There are several types of bombs.
Blocks	Larger Than 64mm (2½ in.)	Erupted fragments of solid rock, usually angular and equidimensional but some are slabby or platey.

*In some tables the range is given as 4mm to 32mm.

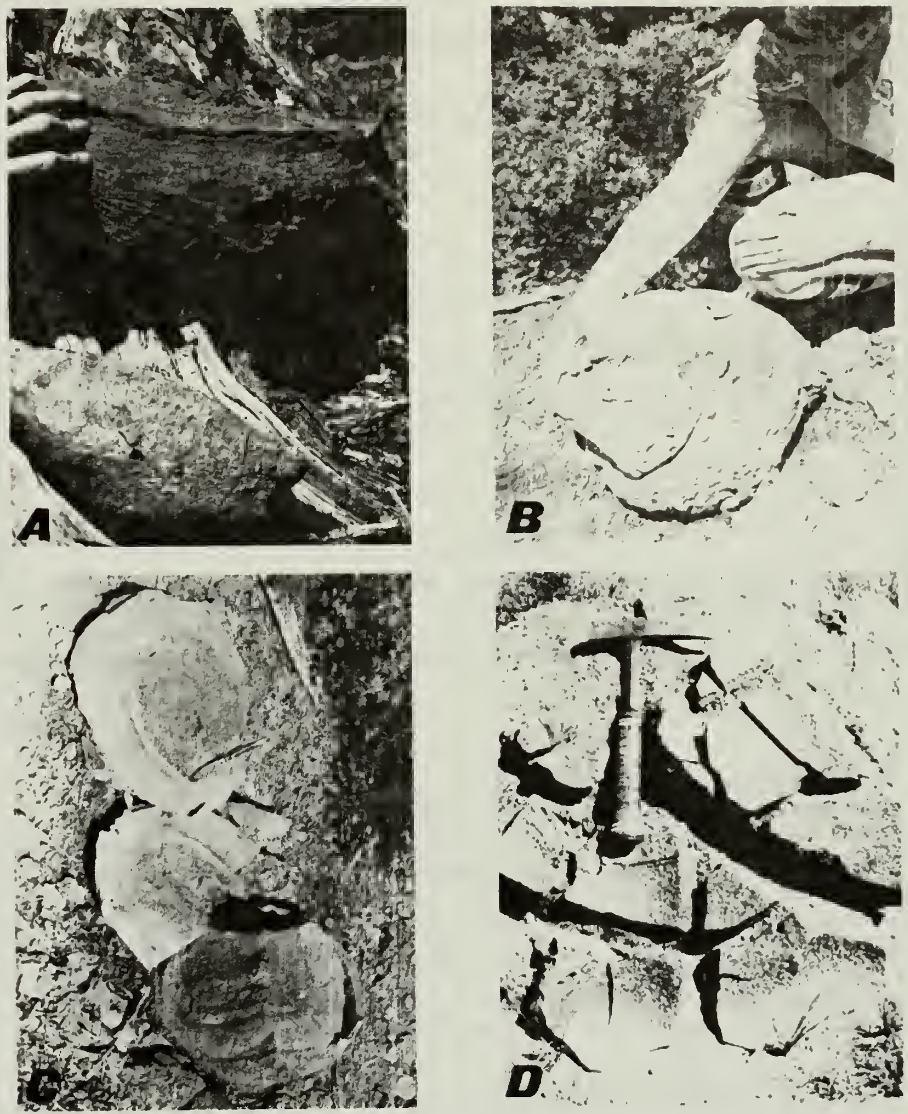
Two other terms are also used in the discussion of tephra; pumice and cinders (Picture 2-6). When hot, fluid rock is thick and experiences a sudden release of

2-3 VOLCANIC ASH The smallest size tephra particles are readily carried by the wind for great distances. Although it often looks like sand, its composition proves its volcanic origin. Scale: each square = 0.5 cm (1/4 inch).

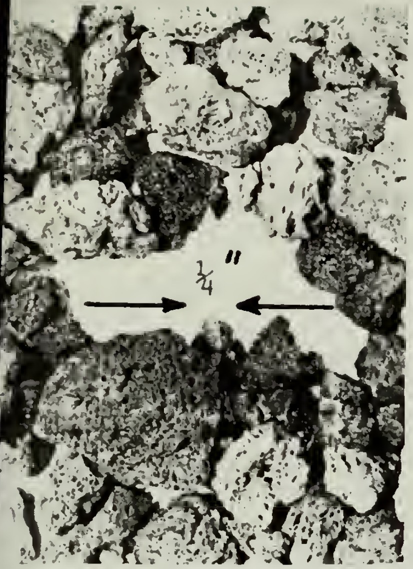


2-4 LAPILLI "Popcorn" pumice deposited along the Rim Drive near Cloud Cap Junction is coarse lapilli of final eruption ejecta. Hammer head is 18 cm (7 inches) long.

pressure, causing rapid cooling, the escape of gas is inhibited. The result is a glassy rock in which, like any liquid that cools quickly, crystals do not have time to develop. A sponge-like structure results with most of the volume occupied by empty space separated by thin glass membranes. This is pumice. Cinders, or scoria as they are commonly called, have much the same history. The basic difference is in the amount of empty space present and the chemical composition of the rock. Since the original material that forms into scoria is mostly fluid, trapped gases escape more readily and thus there is less void space and more rock material. Also, as noted in Table 2, cinders are considered to be lapilli while pumice has no particle size connotation. In addition, generally, cinders are associated with lavas having a basaltic to andesitic composition.



2-5 VOLCANIC BOMBS Bombs are formed in many sizes although the smaller ones display the most streamlined shapes. (A) The streamline shape of two bombs, which were fluid when erupted, can be readily seen here, (B) A large spherical bomb, (C) Same example as "B" showing the concentric internal structure that develops upon cooling. The crust has a fine texture due to rapid cooling which becomes coarse toward the center where cooling is slower. (D) Bread crust bombs result from expanding gases causing swelling and cracking of the hardened surface as the inside cools.

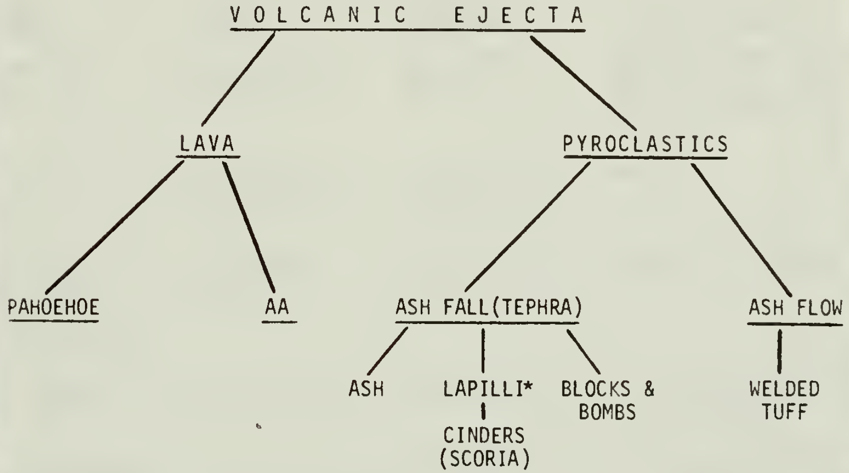


2-6 CINDERS AND PUMICE BLOCKS Cinders have the appearance of tiny "clinkers" and are usually dark colored due to their chemical composition (Fe & Mg content). Pumice may occur as any size particles, ash to blocks, looks spongy, and usually is light colored.

Chemical Composition

Still another factor in understanding Crater Lake rocks is the chemical composition they represent. Volcanic rocks are a type of igneous rock formed by the freezing of hot, liquid material called magma. Since cooling of magma occurs quickly, when it reaches the earth's surface,(where it is called lava) volcanic rocks tend to form extremely small crystals. These are usually too small to see without magnification, although larger crystals, big enough to be easily visible, are often present in lavas. Volcanic rocks are composed of many elements but only a few are abundant; oxygen, silicon, iron, aluminum, calcium, magnesium, sodium, and potassium. Moreover, there is usually far more oxygen and silicon present than all the others combined. As a result, these two elements, expressed as one silicon atom joined with two oxygen atoms (SiO_2), are used to describe the chemical composition of igneous rocks. Table 3 illustrates a simple classification of volcanic rocks and some of the properties associated with certain compositions. The values shown are approximate and, of course, the entire classification scheme is artificial, for there is a continuous range of SiO_2 composition in volcanic rocks from as low as 35% to as high as 75%.

TABLE 2 CLASSIFICATION OF VOLCANIC EJECTA



* The term pumice may be mistakenly used to mean lapilli or block sized particles but really refers to a frothy texture, usually of rhyolite composition.

Cones

When asked to imagine a volcano, most people think of the large picturesque volcanoes commonly used on calendars. Although these beautiful symmetrical cones may represent all volcanoes, at least in people's minds, they are really the exception and few take on this pleasing shape. What then does a typical volcano look like? To answer this question, we must look at different types of volcanoes, formed in different ways and from different material. Let's start by grouping these into four general classes as noted in Table 4.

Two of the best examples of composite cones are Mount Fuji in Japan and Mount Mayon in the Philippines. Both are often seen on calendars or travel posters. Most composite cones, however, do not possess the symmetry illustrated by these more ideal examples. Their name, composite volcano, results from the way they were formed. Erupted volcanic material ranges from basalt to andesite to rhyolite but most fall in the andesite composition category. Another reason for this name has to do with the types of eruptions that build the cone. Although the bulk of volcanic material making up a com-

TABLE 3 VOLCANIC ROCKS AND SOME OF THEIR PROPERTIES

NAME	SiO_2	COLOR	AMOUNT OF GAS	NATURE OF LAVA
Rhyolite	70% or more	light (buff or tan)	high	very thick (seldom flows) Fe & Mg poor (<3%)
Dacite	65%			
Andesite	60%	medium (grey)	medium	flows slowly
Basaltic-Andesite	55%			
Basalt	50% or less	dark (black or green)	low	fluid (flows easily) Fe & Mg rich (up to 5%)

posite cone is lava, pyroclastics are also important in their construction. In examining the volcanic ejecta which build up composite cones, it is not unusual to find lava flows interspersed with pyroclastic layers. The shape and slope of these cones develop because of this more or less alternate layering nature. Lavas tend to flow easily and produce a flattened profile while the pyroclastic deposits build a steeper slope (Figure 2-7)

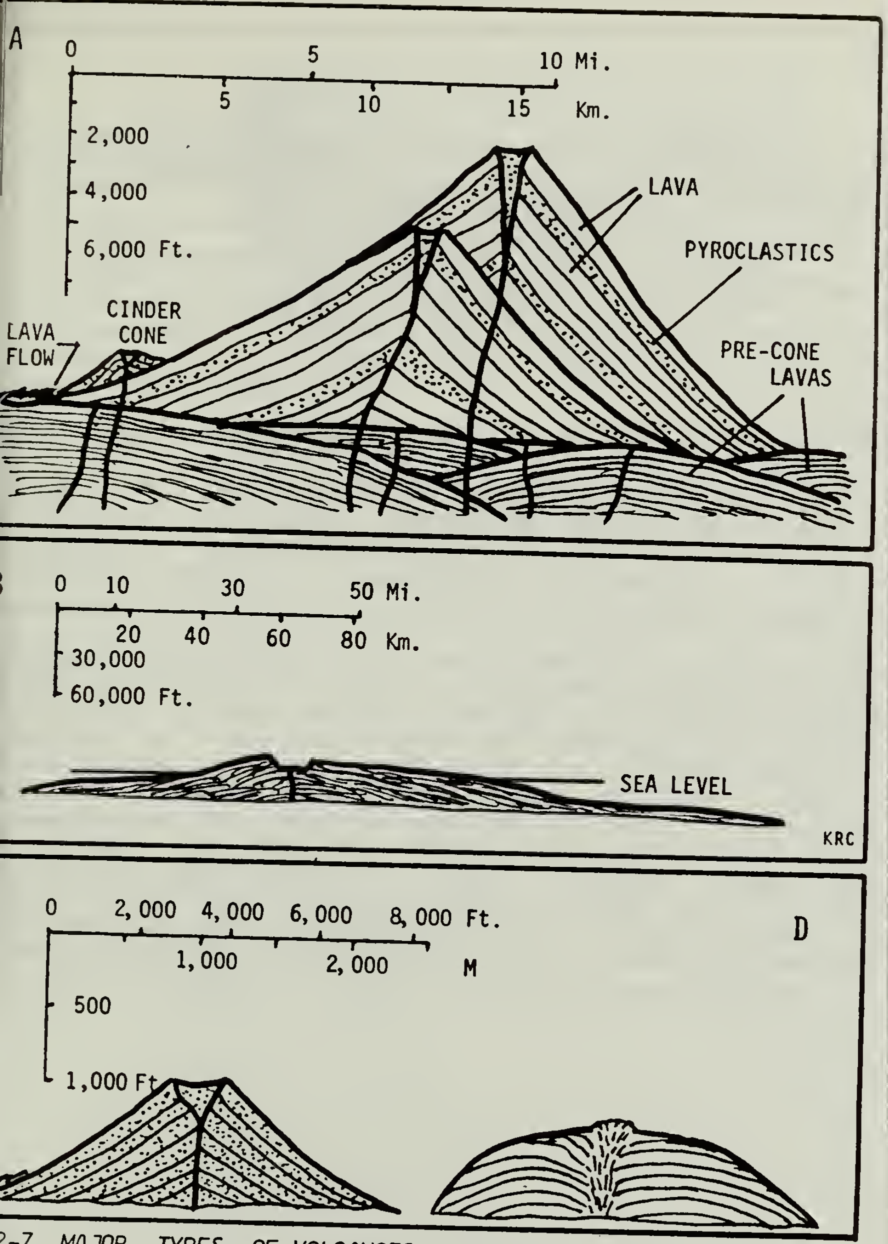
When the volcanic ejecta is mostly basaltic lava flows, composed of quite fluid magma, a low mound shaped cone develops. These are generally called shield volcanoes but may be given other names such as lava cones. Hundreds or thousands of individual flows, each being only a few feet thick, are responsible for building shield cones. The largest volcanoes on earth, indeed in the solar system, are of this type. Although some pyroclastic material, in the form of scoria, is often erupted during the construction of a shield cone, the amount is insignificant when compared to the basaltic lava flows. The massive piles of volcanic material in the Pacific Ocean known as the Hawaiian Islands are classic examples of this volcanic type.

TABLE 4 TYPES OF VOLCANOES

NAME	SIZE		TYPE OF MATERIAL
	HEIGHT	DIAMETER	
Composite	up to 3,600 m (12,000 ft.)	up to 40 Km (25 mi.)	Basalt to Rhyolite Major portions are Andesite & Rhyolite
Shield	up to 9,000 m (30,000 ft.)*	up to 160 Km (100 mi.)	Basalt
Cinder (or Scoria)	up to 350 m (1,200 ft.)	up to 1,600 Km (1 mi.)	Basalt to Andesite
Miscellaneous			
Domes	about the same as Cinder Cones		'Fluid' Dacite / Rhyolite
Ash Rings	about the same as Cinder Cones (usually formed in water)		Pyroclastic Dacite/ Rhyolite

*The Island of Hawaii, at about 9,000 m above the ocean floor, represents the tallest mountain in the world.

If we move to the other end of the spectrum and examine the volcanoes that are composed primarily of pyroclastic ejecta, we are looking at cinder cones. These small vents are perhaps the most abundant type in the world for they form by the hundreds in any given volcanic region. For example, there are over 400 cinder cones in the Oregon section of the Cascade Range. Cinder cones seem to develop in two stages; 1) an explosive period which exhausts the gas stored in the erupting magma followed by 2) quiet lava flows in a late eruptive stage. Although the lavas may be abundant in some cases, the much greater portion of these volcanic cones is composed of pyroclastic ejecta. Although all sizes of tephra are present, lapilli-size cinders seem to be dominant with a good representation of small blocks and bombs. The late lava stage(s) seldom erupt from the upper portion of the cone but commonly break out at the base only to flow away. Cinder cones have rather short histories when compared to the large volcanoes. From the time of the initial eruption to its final sign of life, a cinder cone may be active for only a few tens of years. They seldom, if ever, renew eruptions after a long period of dormancy.



2-7 *MAJOR TYPES OF VOLCANOES Schematic cross sections of he four types of volcanic cones found in Crater Lake ational Park. (A) Composite cone showing a complex con-tructional history. (B) Large shield cone similar to the awaiian Islands. (C) Cinder cone with associated basal lava low at lower left. (D) Dacite dome. Notice the horizontal nd vertical scales for comparisons.*

The discussion above describes the three most common types of volcanoes; the composite, the shield, and the cinder cones. There are, however, many others that are less abundant but equally interesting. One of these, usually called a dome (or rhyolite dome), is not so much a volcanic cone as it is a "blister" formed by extremely thick lava. Upon reaching the earth's surface this magma is too thick to flow, so it erupts by squeezing up and freezing to form a mound.

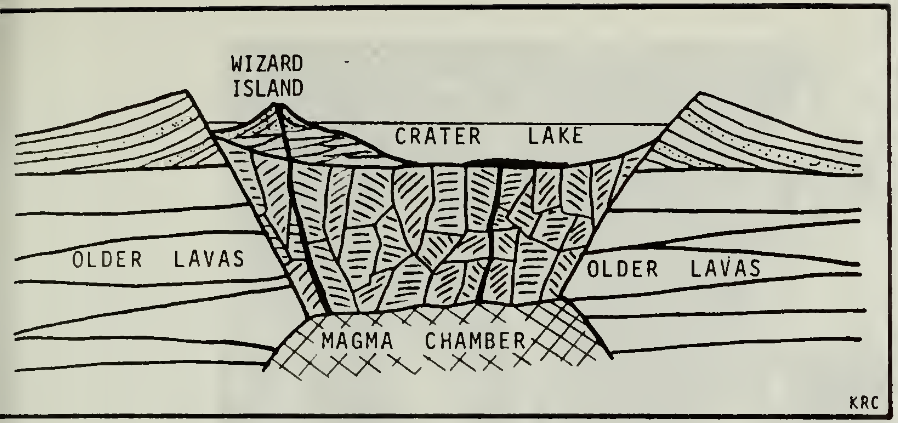
The volcanic cones found in the Crater Lake region are confined to these four types. It should be noted, however, that large amounts of magma reach the earth's surface through fissures that do not construct volcanic cones at all. The great mass of basaltic lava making up the Columbia Plateau and Snake River Plains was formed by such fissure flows. Magma rising along the Cascade Range, however, tend to produce volcanic cones rather than massive lava flows.

Craters

Another rather common impression shared about volcanoes is the way that eruptions occur. It is assumed that volcanic material is ejected from the top or main vent portion of an active volcano. This upper area, or crater as it's properly called, does produce large amounts of ejecta but eruptions may also occur from other places on the cone. Lava may break out on the sides of a composite or shield cone to produce flank eruptions. Sometimes these flank vents result in the construction of small parasitic cones, such as The Watchman and Hillman Peak, to be discussed in a following chapter. Mount Scott may also be considered as a parasitic cone to Mount Mazama although it is rather large to be placed in such a category. With changing conditions within the volcanoe's interior, the vent region may also be affected causing eruptions from new or different parts of the summit. Many of the shield cones and large composite cones have several craters, with activity in one or the other at different times. It must be noted though, that these vents are rather small, usually less than a kilometer (0.75 mile) across.

Calderas

Some volcanoes develop a large depression in the summit area. Such features are known as calderas and



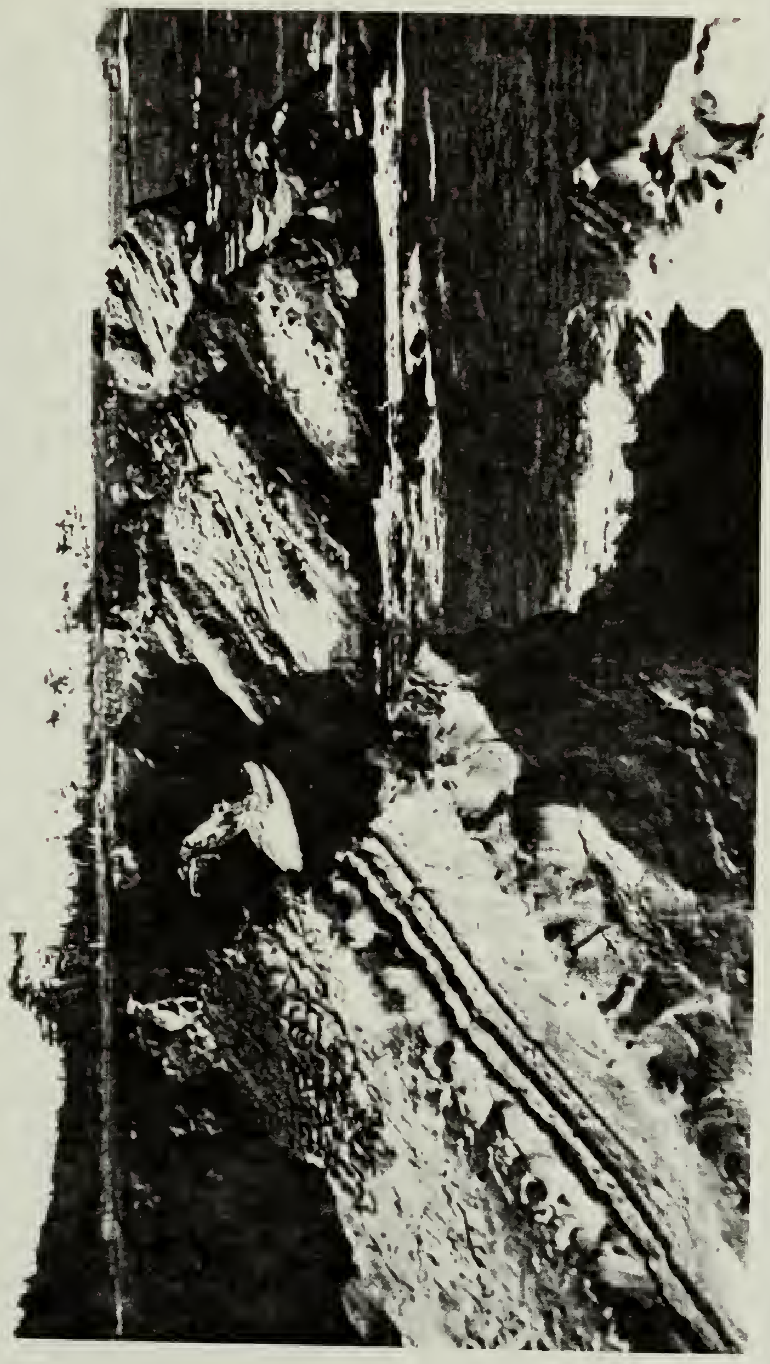
2-8 CRATER LAKE CALDERA A hypothetical cross-section of the Crater Lake Caldera illustrating the collapsed area above the magma chamber. Wizard Island's structure and the collapsed area are only suggestive in this sketch.

epresent exceptionally strong volcanic activity, far
eyond the normal activity that is typical of crater
ruptions. In many cases, calderas have formed by rapid
jection of massive amounts of pyroclasltic material
hich caused the upper portion of the volcanic cone to
ollapse (Figure 2-8). Dr. Howel Williams clearly
emonstrated this process when he studied the geology
f Crater Lake National Park. Although he didn't ori-
inate the basic concept of how a caldera forms, his
tudy found Crater Lake to be one of the world's clas-
ic examples of a caldera. There may be much larger or
omewhat smaller calderas than Crater Lake, but few are
s well preserved or illustrate the process better.

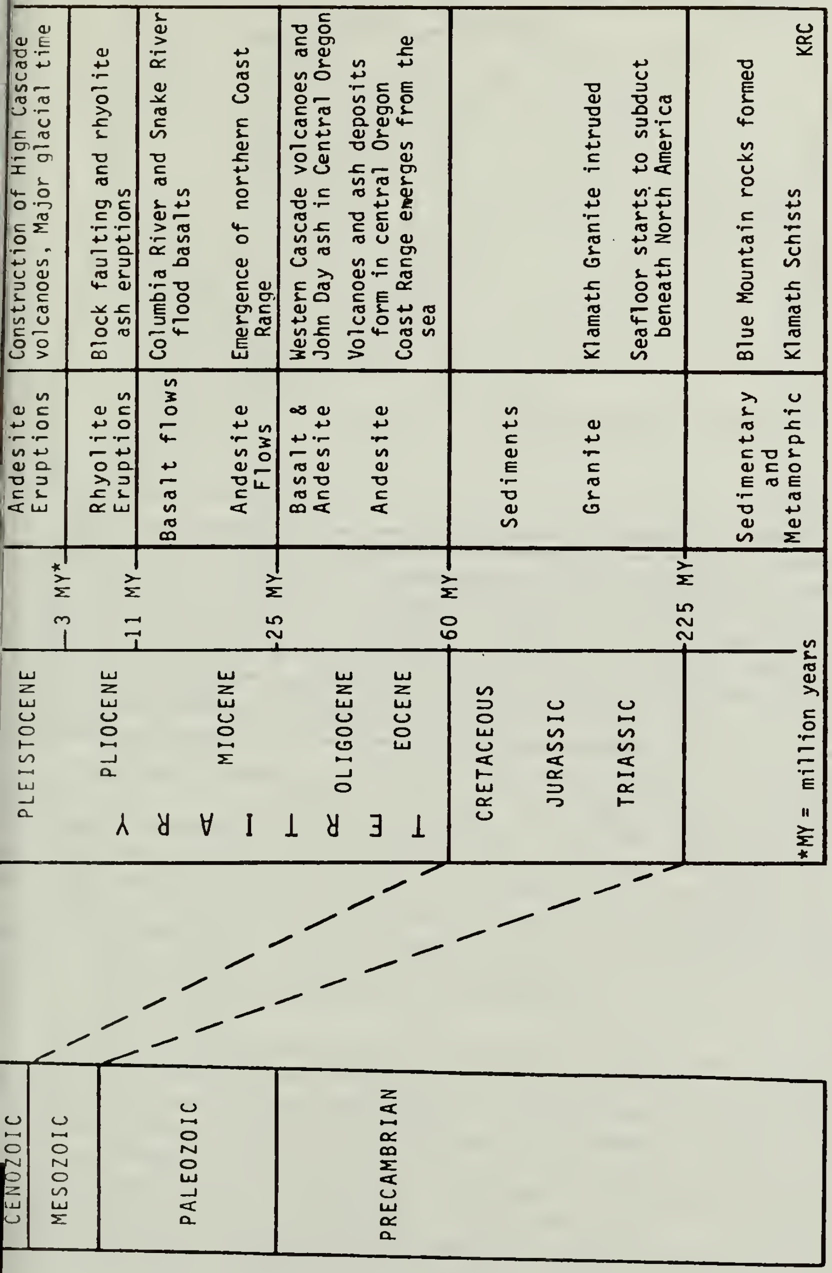
Chapter 3
Before Mount Mazama

The life span of Mount Mazama, the large Cascade composite cone that stood on the site of Crater Lake, was relatively short as geological time is reckoned. It was built in less than a million years and will be discussed in detail in Chapter Four. Geological history of Oregon and the Pacific Northwest, however, is much longer, stretching back at least 200 million years. Since such long periods of time are involved, geologists use a calendar-like chart to help organize these events. This device, called the Geological Time Scale, is divided into major blocks of time which are subsequently divided into smaller time periods. As noted in Figure 3-2, the geological history of the northwestern United States fits into two Eras known as Mesozoic and Cenozoic.

Although there is a larger amount of historical detail that can be drawn into a discussion of Crater Lake, we will confine our discussion to just the basic concepts necessary to understand why and how the High Cascades formed. Very few, if any, of these details can be worked out by looking at the rocks in Crater Lake National Park. Rather, they have been pieced together by many investigators, examining geological features



3-1 DEFORMED SEDIMENTARY ROCKS A large part of Oregon's coast has been constructed by uplifted and folded sediments originally deposited in the offshore trench. Continued movement of the ocean floor under the continent caused these sediments to collapse onto the continent forming the coastal ranges.



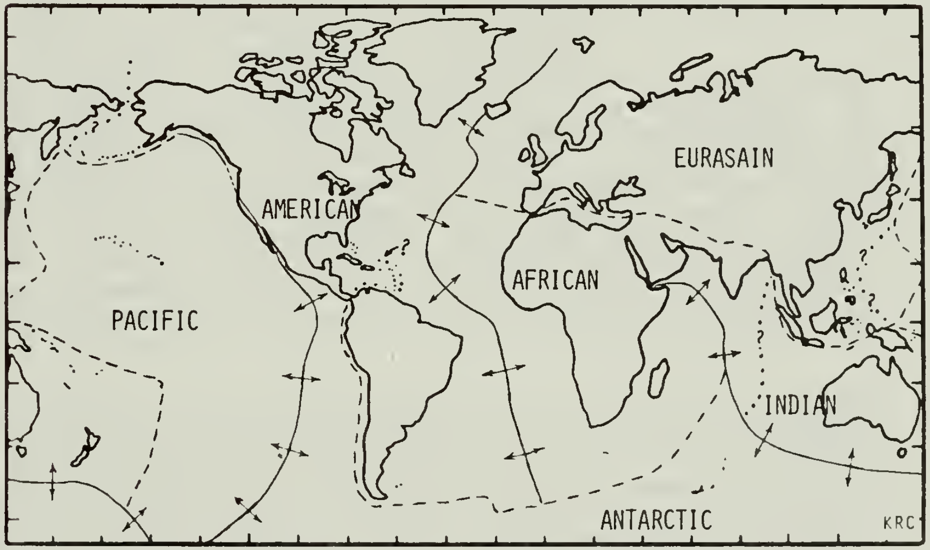
Period	Time	Rocks	Events
PLEISTOCENE	3 MY*	Andesite Eruptions	Construction of High Cascade volcanoes, Major glacial time
PLIOCENE	11 MY	Rhyolite Eruptions	Block faulting and rhyolite ash eruptions
MIOCENE		Basalt flows	Columbia River and Snake River flood basalts
		Andesite Flows	Emergence of northern Coast Range
OLIGOCENE	25 MY	Basalt & Andesite	Western Cascade volcanoes and John Day ash in Central Oregon
EOCENE		Andesite	Volcanoes and ash deposits form in central Oregon Coast Range emerges from the sea
CRETACEOUS	60 MY	Sediments	
JURASSIC		Granite	Klamath Granite intruded
TRIASSIC			Seafloor starts to subduct beneath North America
	225 MY	Sedimentary and Metamorphic	Blue Mountain rocks formed Klamath Schists

3-2 GEOLOGICAL TIME SCALE FOR OREGON

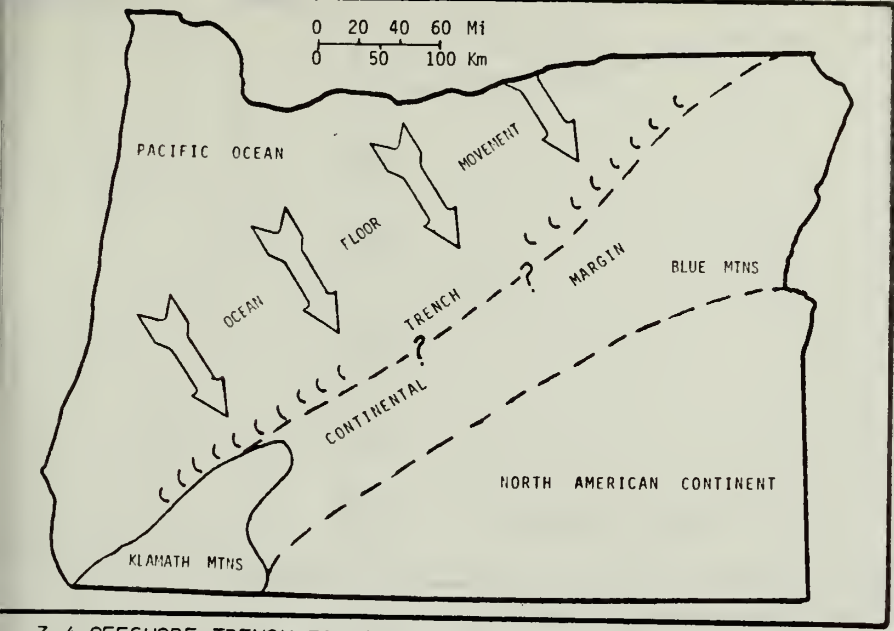
all over the Pacific Northwest. Even with this diversity of evidence and people, there is still a good deal of uncertainty about some aspects of the geology that can be seen here. This does not stop geologists and others from attempting explanations, but most of these are best reviewed as proposed models to see how well the real geology fits. So, when reading, seeing, or hearing any geological explanation, (including this book), try to keep in mind the tentative nature of such matters.

Regional Geology

In recent years a rather astonishing theory has been developed which offers an explanation for many of the earth's features that have long puzzled geologists, geophysicists, and oceanographers. One such mystery questions why volcanoes only occur in certain places on the earth's surface, usually in linear patterns. A similar question centers on the location of earthquakes. Although earthquakes are rare in the Cascades, this mountain system does represent a major volcanic chain.



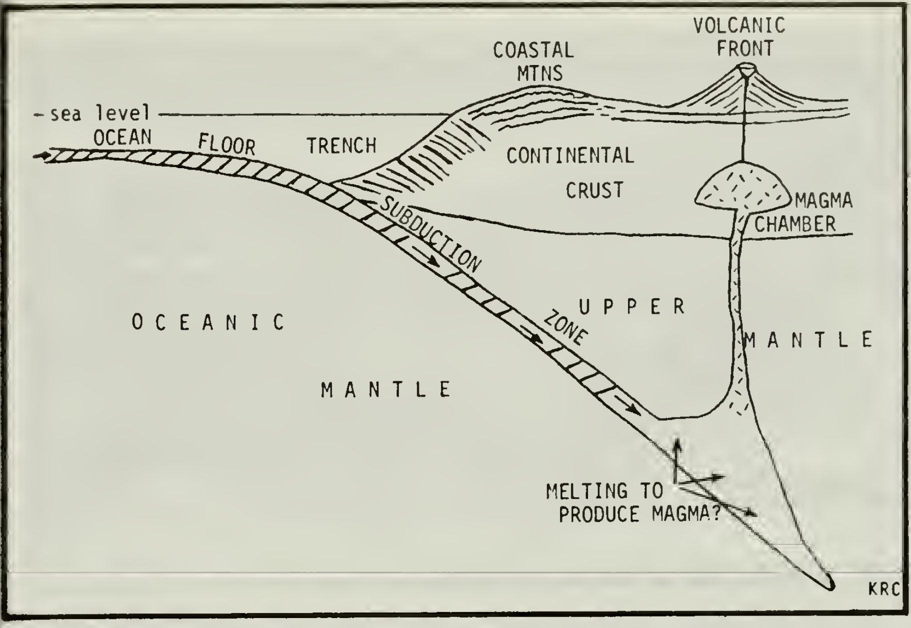
3-3 MAJOR PLATES The earth's surface is composed of six major plates separated by mid-ocean ridges (⟷) and trenches (subduction zones, - - -). New crust wells up from the mantle along the ridges, moves away, and eventually slides back beneath the crust at subduction zones.



3-4 OFFSHORE TRENCH FORMS Approximately 200 million years ago the Pacific Ocean floor started slipping under the North American Continent in the Oregon region. The older mountains, forming a SW - NE trend, may have resulted from sediments, originally deposited in this trench, being pushed up onto the continental margin by the moving sea floor.

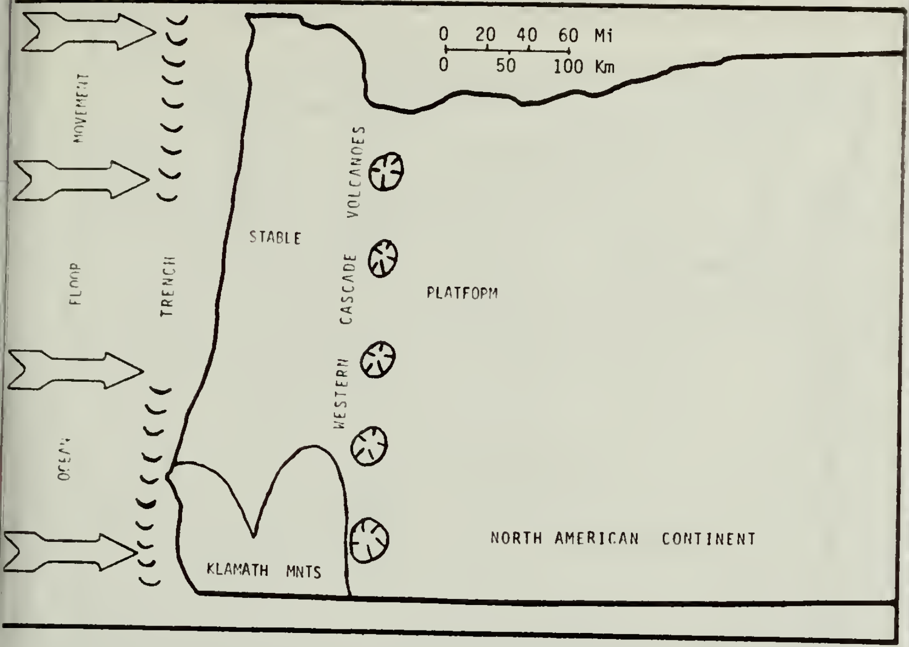
This new theory has come to be known as Plate ectonics. It suggests that the earth's surface is omposed of several large regions, called plates, that re moving with respect to one another (Figure 3-3). uch movement may involve the separation, collision or sliding of one plate with respect to another where hey join. Most of the interesting and dramatic geolog-cal activities associated with the earth's surface ake place along these plate boundaries.

Long before the large volcanoes, known as the High ascades, were constructed, a subduction zone is hought to have developed where Oregon now occurs. This esulted when a portion of basaltic ocean floor slab, iding under the North American Continent, formed a ench located diagonally across the state from the uthwest to the northeast (Figure 3-4). Sediments oded from the continental margin, accumulated in this fshore trench, and were carried along with the moving ean floor towards the continent. As the ocean slab sank beneath the edge of Oregon, this accumulation of sandstone, shale and other sediments was scraped off and pushed up into coastal mountains. Strong pressures along with high temperatures caused these sediments to deform and alter to metamorphic rocks. Today, after much erosion, these highly deformed and altered rocks make up some of the oldest geologic regions in Oregon. The Klamath Mountains in the southwest and the Blue Mountains along the Idaho boarder are representative of this process.



3-5 SUBDUCTION ZONE CROSS SECTION As the basaltic ocean floor moves beneath the continental margin, it encounters a region of greatly increased temperature and pressure. This process may produce magma which eventually rises to the surface to erupt as volcanoes or fissure flows.

During this time, when nearly half of Oregon was covered by an ocean northwest of the subduction zone trench, volcanoes also developed along the continental margin southeast of this trench. There seems to be a strong relationship between subduction zones and volcanic chains. The exact cause of volcanism is not clear but it appears that magma is somehow produced by the down-going oceanic slab. As temperature and pressure increased on this basaltic rock and the overlying continental mantle, melting occurred. The liquid produced should migrate upward as it is lighter than the sur-

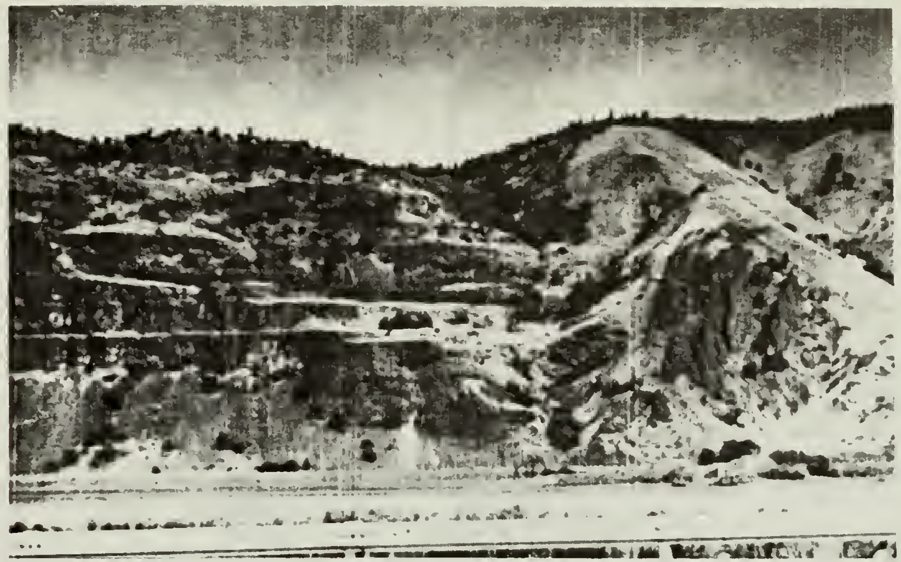


3-6 NEW TRENCH FORMS A second trench developed parallel to the present shore line and accumulated sediments washed in from the continent. These were later added to the continent to form a youthful coast range and the Willamette Valley.

ounding rock. Part of the uncertainty occurs in trying o determine if the magma is created in the slab, beween the slab and mantle, or in the upper mantle beeath the crust (Figure 3-5). Another problem in undertanding this mechanism is encountered as the fluid oves toward the earth's surface. Is it hot enough to ause melting of rocks near the surface thus changing ts chemical composition, or does erupted lava repreent the original melted rock that was formed in the ubduction zone? Regardless of which set of conditions s correct, the result at the surface is the same; the ava that pours out is usually andesite and rhyolite. nd although there is little evidence left of these arly volcanoes, they should have formed on the contiental side of this subduction zone with a composition f andesite, rhyolite and some basalts.

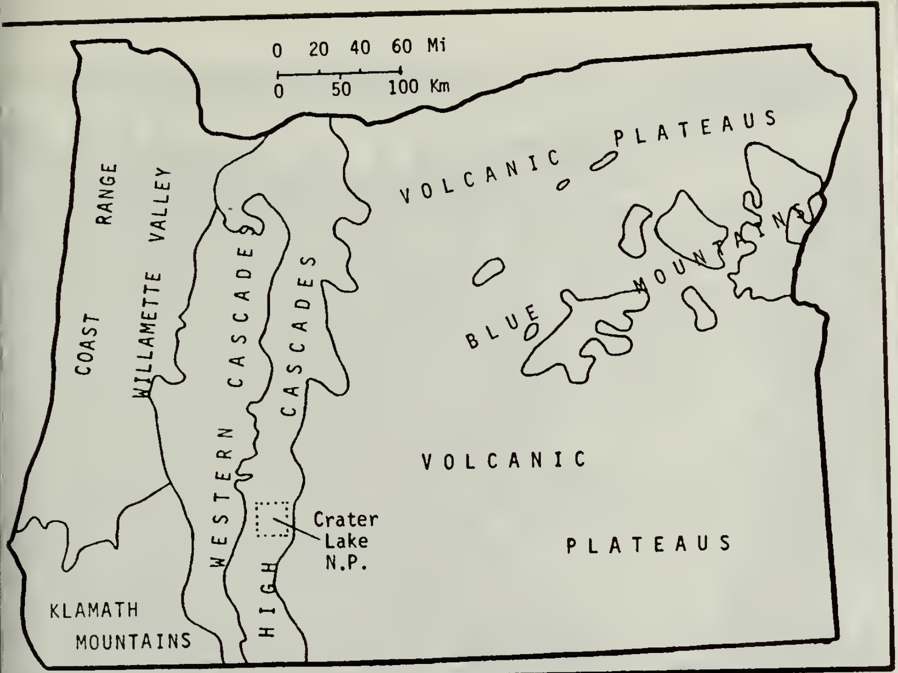
regon Geology

Oregon's landscape, as seen today, developed much ater than the 200 million year old mountains discussed



3-7 COLUMBIA RIVER GORGE These fissure lava flows are up to 1.5 km (1 mi) thick and buried 130,000 sq km (50,000 sq mi) of the earth's surface. Layer upon layer of lava can be seen in the gorge but these flows never extended as far south as Crater Lake.

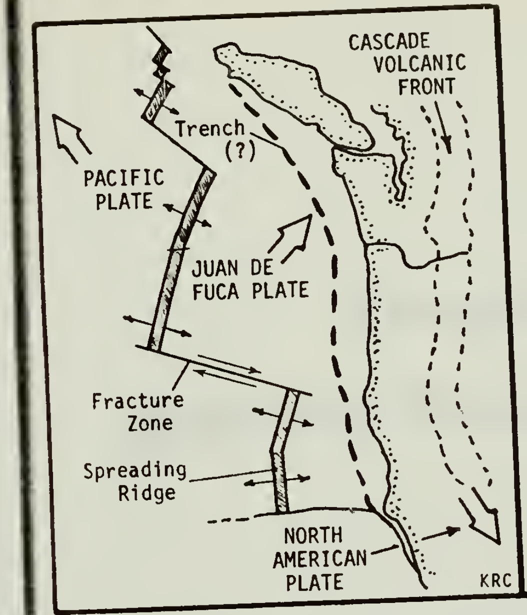
above. The curving subduction zone that cut diagonally across the state seems to have moved to another area located parallel to the present coast (Figure 3-6). This new geological development, starting about 35 million years ago, caused a trench to form (along with an accumulation of sediments) much as the older coastline had done during the early Mesozoic Era. That portion of Oregon between the old and new subduction zones rapidly developed into a stable platform which would allow the balance of the state to form. One way to think of this newly formed northwestern section is simply that it was added to the continent and became part of North America. Other geological features also formed because of the subduction zone's shift in location. A new chain of volcanoes occurred in the location of the present Western Cascade Province and appeared to last for nearly ten million years. Eruptions were highly gas charged, exceedingly explosive, and produced great amounts of pyroclastic ejecta. Much of this material was carried eastward and deposited on the recently stabalized sea floor, resulting in a thick blanket of ash over most of central Oregon.



3-8 OREGON TODAY Major physiographic features of Oregon illustrate the long geological history of the state.

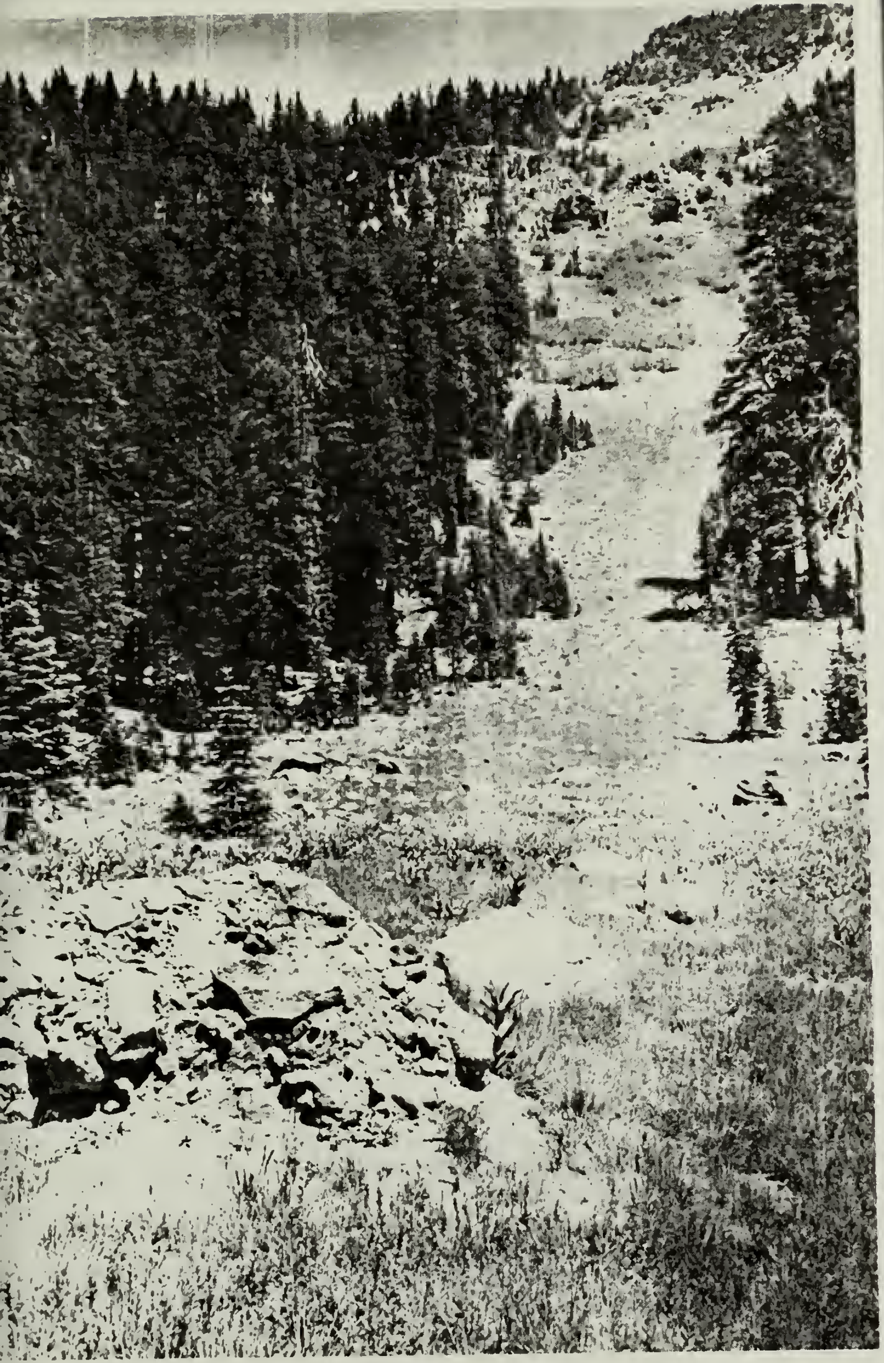
As this series of volcanoes was dying down, a new evelopment can be read in the rock record. Volcanic ctivity in central and eastern Oregon began. These ruptions were quite different from those of preceeding pisodes for the lava was entirely basaltic. In addiion to a change in the kind of rocks formed, there was lso a change in the amount produced. This great flood f basalt buried nearly everything east of the Western ascades leaving only the higher parts of the old mounains exposed in northeastern Oregon. Even today a arge part of the Pacific Northwest has surfaces comosed of the weathering and eroding lavas poured out hirteen to sixteen million years ago. These are specially well exposed in the Columbia River Gorge etween Washington and Oregon (Picture 3-7). With the ventual cessation of these massive basaltic flows, olcanism resumed in a linear pattern along the Western ascades. Thus, the much younger Western Cascade volanoes that are visible today were constructed on top f an older volcanic mountain system starting about twelve million years ago.

With the construction of the Western Cascades, Oregon began to take on its present day appearance. There is, however, one last area to develop before the High Cascades can be considered. Like the older mountains formed some 200 million years ago, the coast range mountains were pushed up by the slowly moving ocean floor continuously sliding beneath the continent. This caused the thick accumulation of sediments, that had been eroded from the land and transported to the trench, to be scraped off and slowly jammed against the continental margin (Picture 3-1). The present day coastal mountains began rising along the southern Oregon shoreline just north of the Klamath Mountains. Uplifting continued to the north, forming an elongated basin on the east side, which subsequently became the Willamette Valley (Figure 3-8).



3-9 VOLCANIC FRONT The High Cascades form a volcanic front resulting from the Juan De Fuca Plate colliding with the North American Plate to produce an offshore subduction zone (trench?).

At this point in Oregon's geological history, a million years ago, all major land forms were in place. The stage was set for construction of the High Cascade volcanic chain which dominates the landscape today. This relatively new episode of volcanism has continued until the present. Before this new stage, most of the volcanoes that marked the north-south chain; the Western Cascades, had been predominantly shield cones. These older cones have, of course, suffered significant amounts of erosion and can seldom be identified as shield volcanoes. Their composition, almost entirely of basalt flows, is a good indicator, however. As we look at recent construction of the High Cascades, in Chapter Four, we must keep in mind that the great North American Ice Age played a major role in producing the Oregon that we see today. On to the High Cascades!

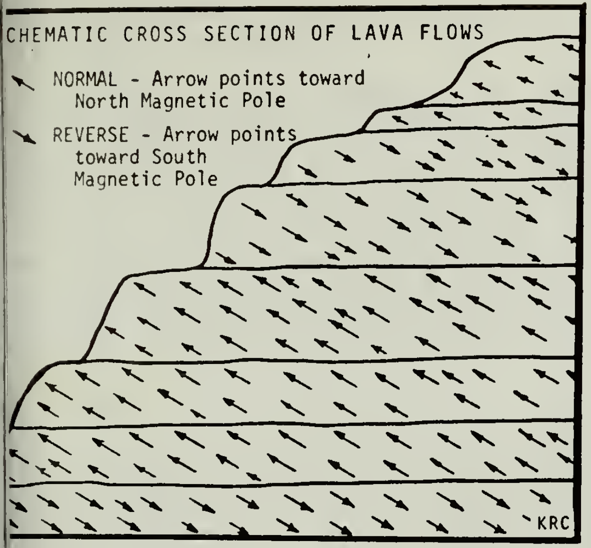


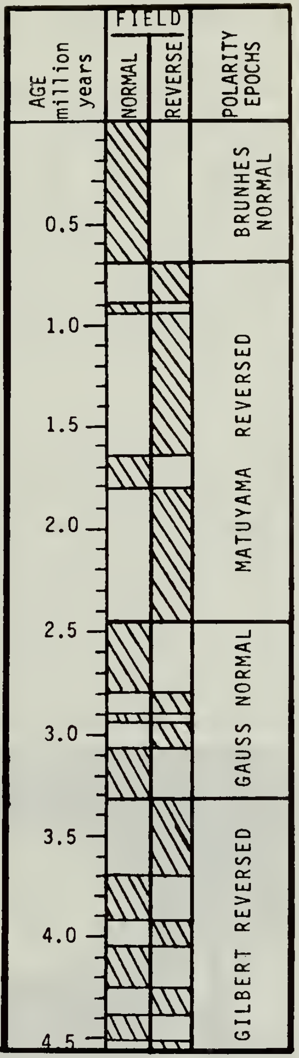
Chapter 4

Building Mount Mazama

Slightly east of the Western Cascades lies the most pronounced volcanic providence in the Pacific Northwest -- the Cascade Mountain Range. Individual volcanoes along this chain have created some of the most spectacular scenery in the United States, if not the world. Volcanoes to the north and south of Oregon tend to be higher than those in the middle portion of the chain. The two tallest peaks; Washington's Mount Rainier, at an elevation of 14,410 feet and California's Mount Shasta, only slightly lower, at 14,261 feet, clearly illustrate this point. The high elevations of this Range are primarily responsible for the climatic variations observed in Oregon today. Moisture laden air moving off the Pacific Ocean flows up and over the High Cascades, resulting in heavy precipitation on the west side but desert conditions prevail on the east. To a great extent, Oregon's landscape has formed within one or the other of these climatic extremes, and continues to develop under the influence of this spectacular series of volcanoes.

4-1 AVALANCHE CHUTE This open strip results from snow and rock debris sliding down slope, a form of mass wastage. Sharon's Rock, at the lower left, represents an unusually large block that has rolled down from its original position in a volcanic breccia high on the ridge.


CHEMATIC CROSS SECTION OF LAVA FLOWS
NORMAL - Arrow points toward North Magnetic Pole
REVERSE - Arrow points toward South Magnetic Pole
KRC



*2 MAGNETIC REVERSALS Tiny magnetic
ystals (↖) in lava flows record the
ientation of the earth's magnetic field.
ey aline parallel to the field before
e lava hardens to preserve the North-
uth directions. By examining the orient-
ion of these natural magnets, the
quence of reversals can be determined.*

*3 GEOMAGNETIC TIME SCALE When ages of
gnetic reversals from a large number of
vas are combined, a distinct pattern
velops. This scale is similar to the
andard Geological Time Scale (Fig 3-2)
t based on magnetic data.*

e Cascade Volcanoes

Until recently, one of these large volcanoes;
unt Mazama, occupied the present site of Crater Lake.
is volcano was constructed in much the same way as
ose still remaining. Learning how one was built and
e type of rocks involved, will provide a reasonably
od idea of the nature of any composite cone along the
gh Cascade Range. Crater Lake offers a better oppor-
nity to determine these facts than any place in the
scades, and perhaps, the entire world.

When did the Cascade composite cones start forming? Just a few years ago geologists would have answered "about two million years ago." More recently, the number being used is 700,000 years or less. This rather dramatic change in the dating of major Cascade peaks is not as unusual as it may first appear. The older figure was based on estimating the age of volcanoes from geological studies in many different areas along the range. By contrast, the 700,000 year upper limit is determined by measurement of the magnetic characteristics of entire lava sequences for a few Cascade volcanoes (Jefferson, Three Sisters, and Mount Mazama). The principle used to determine this younger age is based on the magnetic properties of volcanic rocks. Measurements of tiny magnetic minerals indicate that the earth's magnetic field has reversed or switched directions at certain times in the past (Figure 4-2). When lava is cooling to solid rock, these small minerals act like miniature magnets that line up parallel with the earth's magnetic field, just like a compass needle. When the earth's magnetic field is normal, like today, the north seeking end of these natural compasses point north. If it's reversed; flipped to the opposite direction, the north end would point toward the south pole. The last time the magnetic field reversed was about 700,000 years ago (Figure 4-3). Since all lavas produced by the High Cascade volcanoes have normal orientation, they appear to have formed during the present magnetic orientation, within the last 700,000 years.

Mount Mazama, at Crater Lake, shares this age with the other composite volcanoes that make up the Cascade Range. Likewise, it shares the mode of construction of these other high peaks as well as other similar volcanoes around the world. Most of the volcanic material which built Mount Mazama, was ejected from a central or main vent area. This does not mean that Mount Mazama had only one crater, for as we will see later, there were likely several vents in the summit area. This is the main reason that composite volcanoes, or any volcano, tends to produce an inverted cone shape as they become larger. Still another factor is the relative amounts of lava and pyroclastics produced by the volcano. As noted in Chapter Two, composite cones are built by a mixture of fluid rock and solid debris, more or less alternating during the time of construction. Mount Mazama was no exception to this model, although it appears that more lavas were produced than pyroclastic materials. As a result, it may have been somewhat less steep than some of the other Cascade cones

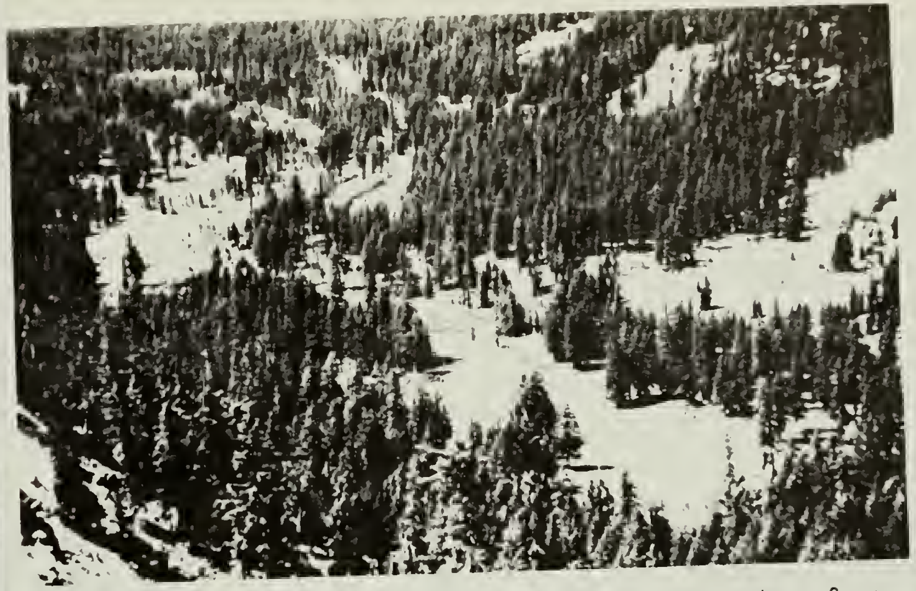
vhich produced a greater percentage of cone steepening yroclastic materials.

So far our discussion of volcanic materials has een uncomplicated with ejecta being either lava or yroclastic debris. The real case is somewhat more omplex, for there are several processes that modify hese products after they have been produced and deosited on the volcanoe's slopes. Although there are any possible ways that ejecta can be reworked or e-deposited, we'll discuss only the major types. These nclude glaciers, running water, and mass wastage; the ownhill movement of loose material due to gravity.

laciation

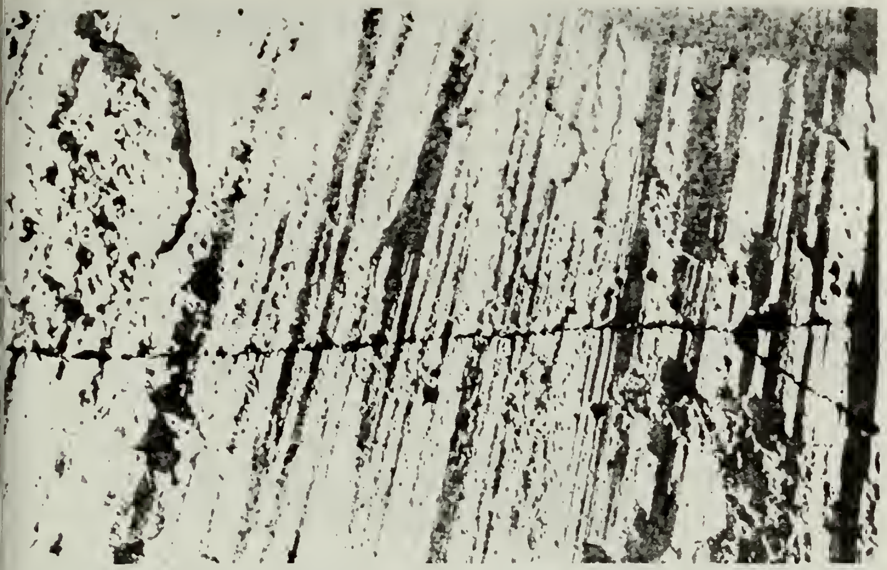
During the time that mount Mazama and the other igh Cascade volcanoes were being constructed, they ere also being eroded by glaciers. The past two-to-hree hundred thousand years have seen four major lacial advances in North America. At higher elevaions, such as the High Cascades, this meant that huge mounts of ice accumulated and moved downhill. At imes, eruptions would produce volcanic ejecta that eposited directly on glacial ice rather than on the ocks below. If these eruptions consisted of hot fluid avas, they would result in melting portions of the ice and, quite likely, explosions in which melt water rapidly converted to steam. Large amounts of water produced from such rapid melting often resulted in catastrophic events; massive flood-like runoffs or mud slides. It was a minor version of such processes that resulted from the most recent eruption of California's Lassen Peak in 1917, to produce the devastated area. Of course the May, 1980 eruption of Mount St. Helens provided an excellent example of this phenomena. Similar or larger events surely occurred as Mount Mazama was being constructed, but evidence to demonstrate such occurrences is difficult to identify now. Much of the pyroclastic ejecta originally deposited on these glaciers was carried away from the central vent, only to be left far down the valleys.

4-4 MOUNT RAINIER Over 25 glaciers presently move down the slopes of Mount Rainier, the largest of the Cascade Composite volcanoes.



4-5 MUNSON VALLEY This view down on Park Headquarters from Garfield Peak illustrates the U-shaped, flat bottomed nature of this glacial valley. The entire Rim Village area was beneath ice when the Munson Glacier filled this valley.

Much of the Crater Lake landscape has resulted from glacial erosion as well as volcanic activity. The Pleistocene Epoch, as noted in Figure 3-2, is commonly called the Ice Age, for it was during this period that glaciers were widespread in the Northwest. Indeed, the Cascade volcanoes were periodically buried in moving tongues of ice during this time. When the climate was cool enough to allow winter accumulations of snow to

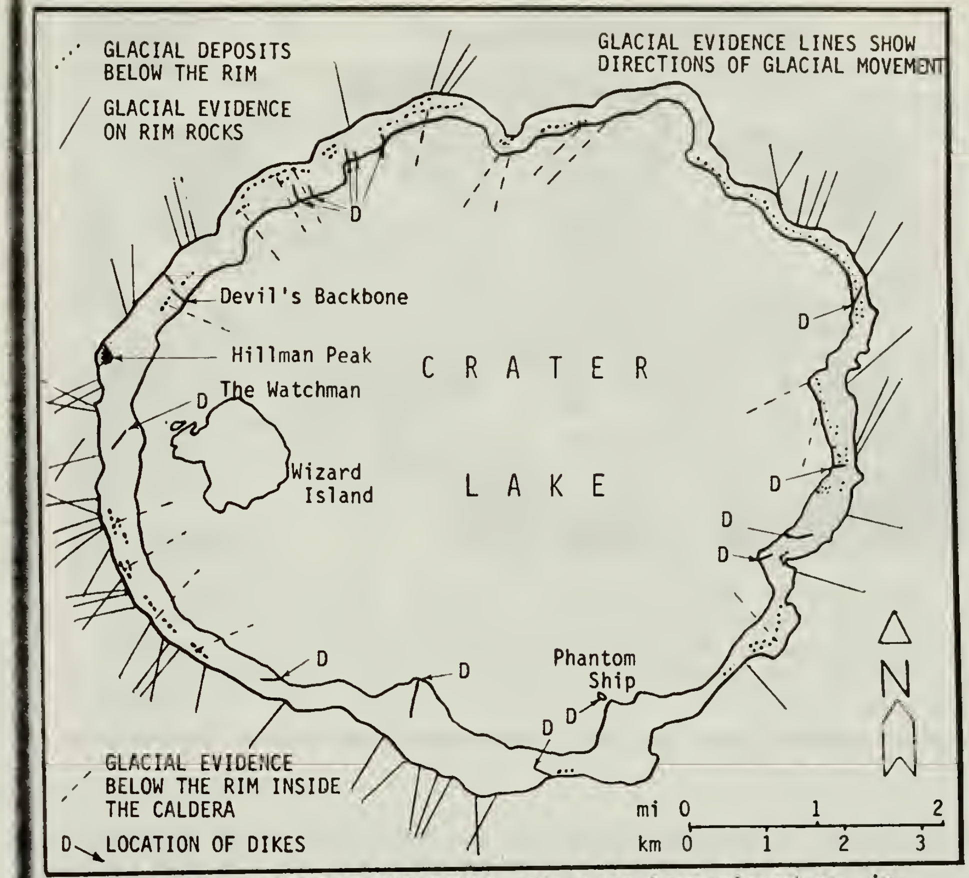


4-6 GLACIAL STRIATIONS In the past, Mount Mazama had glaciers flowing down its flanks to produce scratches and polish. Small patches still remain in several locations on the rim. This example can be seen near North Junction on Rim Drive.

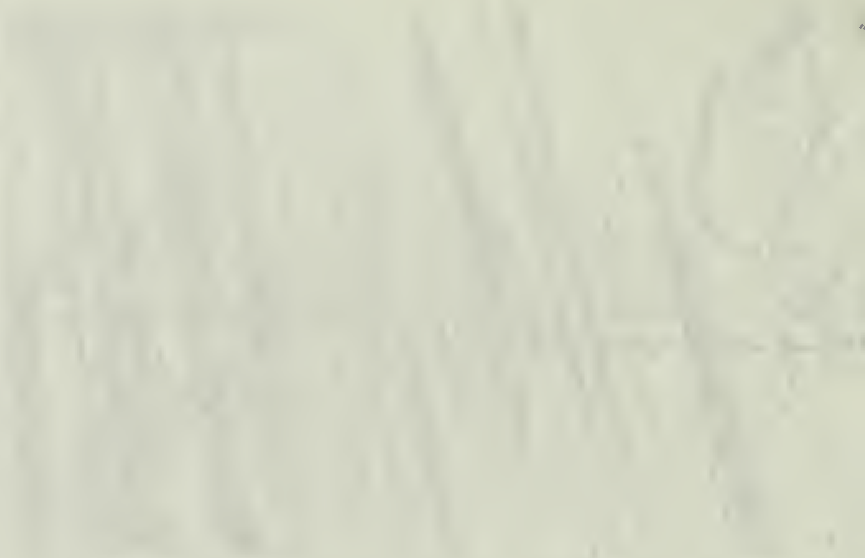
uild up from year to year, glaciers would form and row. Temperatures and snowfall today still nourish emnants of these icy rivers, especially in the Washngton section of the Cascades (Picture 4-4). Farther outh, however, few glaciers exist and their presence n the past must be inferred by other evidence.

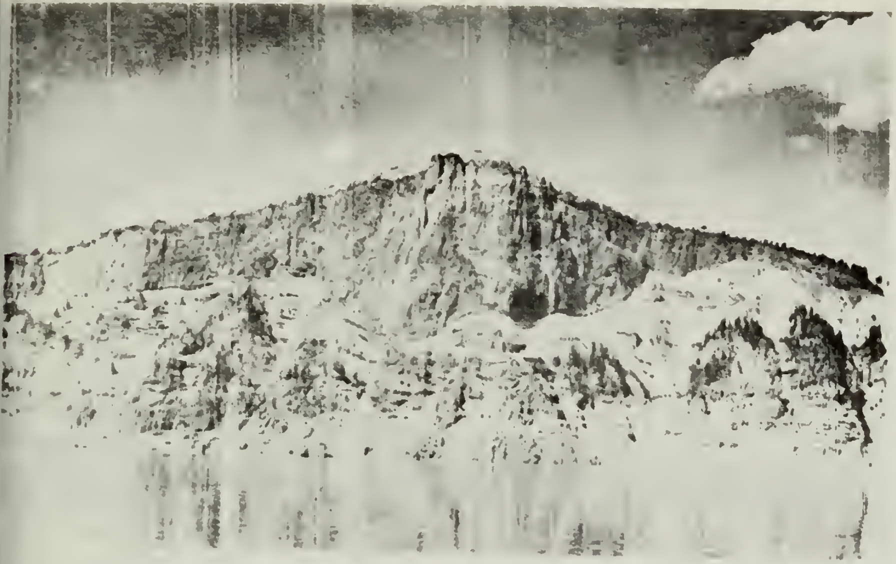
At Crater Lake, direct evidence for valley laciers may be found for much older episodes, as well s those responsible for shaping the present surface. ne of the primary indications of glacial activity in ountains is the U-shaped valleys which display a road, flat bottom. The cross section of Kerr Notch and un Notch, as viewed across the lake, are near perfect xamples, as is Munson Valley, looking down from the arfield Peak Trail (Picture 4-5). Other low sections f the caldera rim may have been locations where laciers developed and flowed away from Mazama's ummit.

Direct evidence of glacial activity is also indicated by the glacial striations (scratches) found on he volcanic rocks exposed along the caldera rim (Picture 4-6). These are caused by rocks in the bottom of the ice being dragged across the surface in sandpaper-like fashion. If the rock material being carried is fine, a smoothing or polish-like finish will develop, rather than coarse notches or gouges. Regardless of the size of these features, they provide positive evidence of the direction the ice was flowing as it moved downhill (Map 4-7). Although volcanic rocks do not accept or retain glacial polish as well as other rock types, there are several places where this effect can be clearly seen. Rocks exposed at Discovery Point and near North Junction are good examples with easy access.


GLACIAL DEPOSITS BELOW THE RIM
GLACIAL EVIDENCE ON RIM ROCKS
GLACIAL EVIDENCE LINES SHOW DIRECTIONS OF GLACIAL MOVEMENT
Devil's Backbone
Hillman Peak
The Watchman
Wizard Island
CRATER LAKE
D
Phantom Ship
N
GLACIAL EVIDENCE BELOW THE RIM INSIDE THE CALDERA
LOCATION OF DIKES
mi 0 1 2
km 0 1 2 3

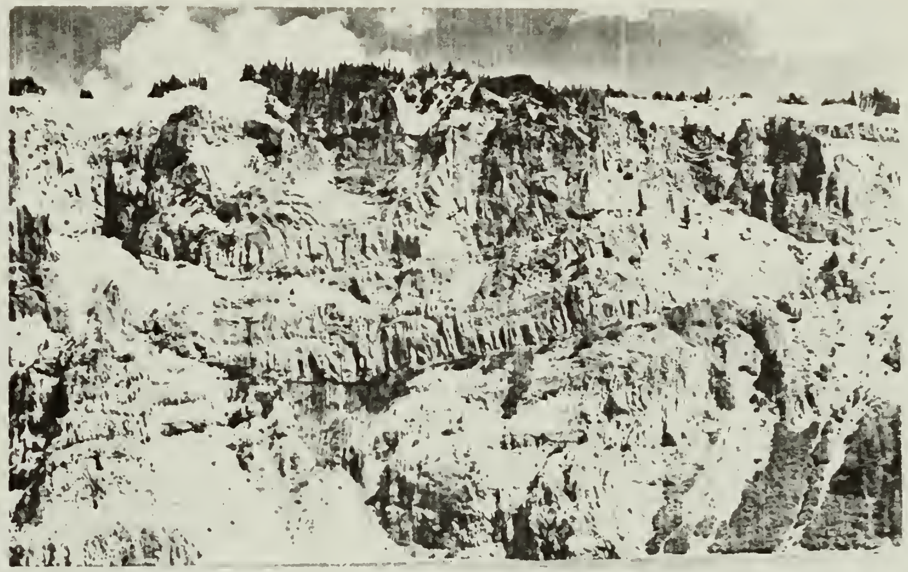
4-7 GLACIAL EVIDENCE AND DIKES Glaciers have played an important role in Mount Mazama's growth. Some of the glacial evidence presented on this map, however, has been reinterpreted and is now thought to represent non-glacial deposits. (after Williams, 1942)





4-8 LLAO ROCK More than half the height of the caldera wall in this picture consists of a single lava flow. This was originally thought to fill a large glacial valley but recent evidence suggests the depression is an explosion crater.

Many of these same features can be seen inside the :aldera representing evidence for glacial activity as Iount Mazama was being constructed. But remember that .ny surface developed while Mount Mazama was actively rowing, such as the U-shaped valleys, will be buried eneath later eruptions. There are examples of buried lacial valleys exposed in the walls of the caldera. 'he job of establishing the presence of a glacial alley requires more than merely finding an appropritely shaped cross section. Positive evidence, like olish, striations, or glacial deposited material, must e found to confirm the presence of glacial activity. eologists in the past have been too eager to assign ome features to a glacial origin. The most obvious xample is Llao Rock (Picture 4-8) which does have a -shaped appearance. Recent studies suggest a completey different explanation for the shape of Llao Rock's valley". Farther east the base of Round Top was also hought to result from glacial activity. When geoloists make close inspection of the area, immediately eneath this large flow, no direct evidence of glacial ctivity can be found. There is, however, evidence of lacial activity in some places along the caldera wall. etailed mapping inside the caldera indicates that glaciers were instrumental in Mount Mazama's construction, but not to the degree attributed to it originally.



4-9 BURIED GLACIAL VALLEYS Shallow glacial valleys have been filled with lava at several different levels in the eastern wall of the caldera. Glacial material beneath the lava may provide a path for water to follow, and springs develop.

Evidence suggests that recent glaciers were large and important erosional agents in certain parts of Mazama. Ice may have exceeded 500 feet in places. Sun Knotch and Kerr Knotch testify to this fact. As glaciers flow, they transport loose rock material ultimately depositing their load at the terminous, somewhat like a giant conveyer belt. The resulting features are known as moraines and serve as direct evidence of glacial activity. Moraines consist of a mixture of rock sizes from extremely fine powder (rock flour) to huge blocks many feet across. Until recently, many of the exposures in the valleys radiating out from Crater Lake, were considered to be glacial deposits. These deposits do have many of the characteristics found in moraines. Careful study by Dr. Charles Bacon, however, has shown them to be volcanic in origin, rather than glacial till. They are related to explosive eruptions and will be discussed in more detail in Chapter Five.

4-10 AVALANCHE DEPOSITS During periods of eruptive activity avalanche material, often as hot debris, was emplaced on Mazama'a slopes and in the valleys. Originally, these were mapped as glacial deposits. This roadcut through avalanche debris near Park Headquarters, was thought to be a small moraine.

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ater and Gravity

Due to its abundance, water is usually the most mportant erosional agent in a humid climate. This is ndoubtedly true for Mount Mazama as it erupted, grew, nd was altered by flowing water. Any glacial valley tarted as a stream valley and was certainly occupied y running water when not filled with ice. But, evience of erosion by water as Mount Mazama was being uilt, is almost nonexistent at the surface today. With he advent of the final eruptions, all these valleys ere buried under many feet of pumice completely conealing the original topography of the volcano. What is een in the park now is water erosion of these pumice eposits, which have occurred in the last few thousand ears. These rather spectacular gorges will be discused in greater detail in Chapter Six.

One of the most widespread agents of erosion is he downward pull of gravity (mass wastage). Since it s present everywhere on the earth's surface, gravity only needs loose rock to be an effective transporting agent. Since much of the volcanic material produced by a composite volcano is loose debris, mass wastage is prevalent on these structures. Whenever the slope becomes too steep to maintain a stable condition, a portion will simply break away and slide downhill as a rock slide or landslide (Picture 4-1). Angles as low as 30 degrees, or even less, are steep enough to allow mass wastage to occur.

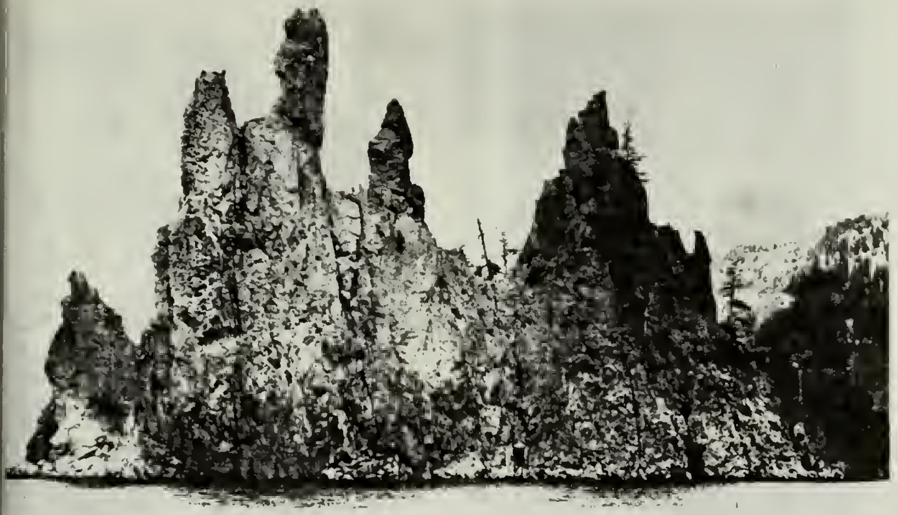
Factors that affect how mass wastage occurs, include many conditions such as the type of debris and the slope angle. Angular blocks tend to be less likely to move than more rounded shapes. Water, however, may be the most critical influence in allowing movement to occur. Generally, the greater the percentage of water in loose rock material, the easier it will respond to gravitational forces. As a result, water saturated debris may move down slopes of only a few degrees as a semi-fluid mass.

Inside the Caldera

One of the reasons Crater Lake is so pleasing to the eye is the high walls which confines the lake on all sides. It's this same feature that provides much of the evidence for geologists who are trying to reconstruct how Mount Mazama was originally built. Although the basic nature of a composite volcano is described in Chapter Two, the details displayed in the caldera walls indicate a much more complex geological history for Mazama. Much of this evidence can only be appreciated from lake level. And the boat tours offer the best method for examining the geology exposed in the caldera walls.

Along the southeastern caldera wall, directly opposite the Phantom Ship, the exposed rocks are some of the oldest in the park. By use of modern dating methods, a tentative age of 300,000 years has been measured for rocks found low on the caldera wall in this area. Although these rocks probably do not represent the original eruptions of Mount Mazama, they appear to be the oldest presently exposed and seem to be part of an early volcano which occupied this site.

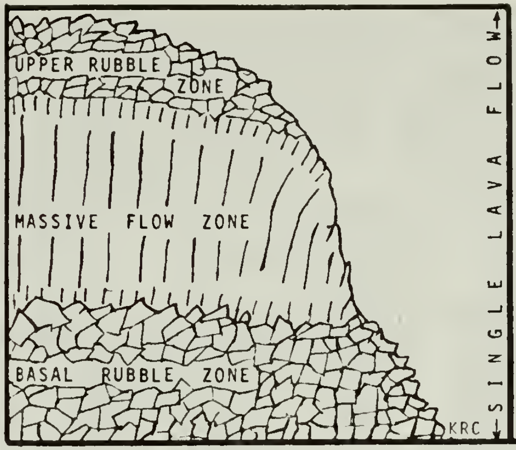
This small cone has been given the name "Phantom Cone" because the Phantom Ship composes a portion of the feature. By observing the caldera wall below Dutton Cliff, a good cross-section of this early structure can



4-11 PHANTOM SHIP As the small Phantom Cone was intruded by magma, dikes were formed. The "sails" represent one such dike which resists weathering better than the lava that composes the base of Phantom Ship.

e seen, comprising about halt the distance from water evel to the rim. Much younger lavas lap upon the hantom Cone from the east, in a rather pronounced slope in this wall. Also, some of the pinnacle-like eatures are thought to represent magma that filled in he vent of this volcano. The Phantom Ship, as part of his feature, has "sails" that were formed from dikes utting across the lavas which make up this old cone Picture 4-11).

Other parts of the caldera wall appear younger han this southeastern region. The lower portions of he caldera are composed primarily of andesitic lava flows. Individual flows range from ten to eighty feet hick, but the majority are in the twenty to thirty foot category. From the description of composite volcanoes in Chapter Two, alternate layers of lava and pyroclastic material would be expected in a cross-section, and this is what a typical wall of the Crater Lake caldera looks like upon first examination. The massive dark zones appear to be lava while the lighter, more textured layers seem to be pyroclastic debris. In some places this is the correct interpretation, but there is another explanation for most of these alternate layers exposed in the walls (Figure 4-12).



4-12 AUTO-BRECCIATION This cross-section of a single lava flow shows the three zones which develop as the flow moves. Cooling at the base and the top causes the lava to solidify then break up into rubble zones. The more fluid lava in the middle solidifies after all movement has ceased, resulting in the massive appearance.

When a lava flow moves down slope, the bottom will cool more quickly as heat is rapidly lost to the ground and the liquid rock starts to harden. With the continual movement of the more fluid lava in the central part of the flow, this solidified layer on the bottom tends to break into blocky pieces; a process known as auto-brecciation. As a result, when a cross-section of one of these flows is observed, it appears to be composed of two zones, a lower pyroclastic-looking region, and a lava flow on top. To add an additional complication, the same process may occur in the upper part of the flow. Rapid heat loss to the air also results in formation of a blocky pyroclastic-looking zone on top of the more massive appearing lava. From a distance it's difficult to distinguish these rubble zones from actual pyroclastic deposits. There are good road cuts along Rim Drive that illustrate this process quite well.

With the concept of auto-brecciation in mind, it is easier to believe that most of the layering visible in the caldera walls is actually the result of lava flows and not pyroclastic deposits. This leads to the conclusion that Mount Mazama was constructed primarily of andesite lava flows with far less explosive deposits than is suggested for the origin of composite cones. There are, however, good examples of pyroclastic debris interlayered with lavas at several locations inside the caldera. Both Eagle Craigs (below Garfield Peak) and the wall between Sun Notch and Applegate Peak illustrate the classic layering of composite cones (Picture 4-13).

[illegible]

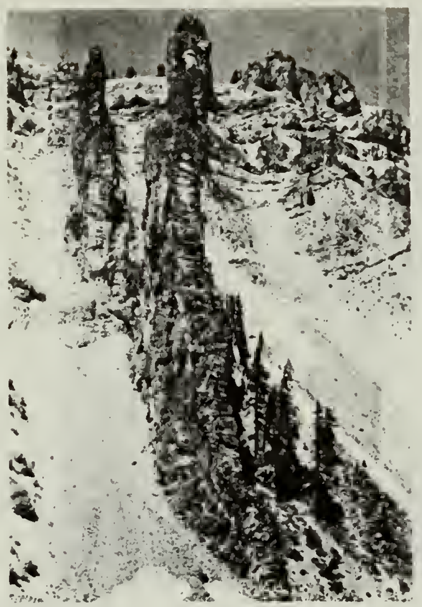
[illegible]

[illegible]

[illegible]

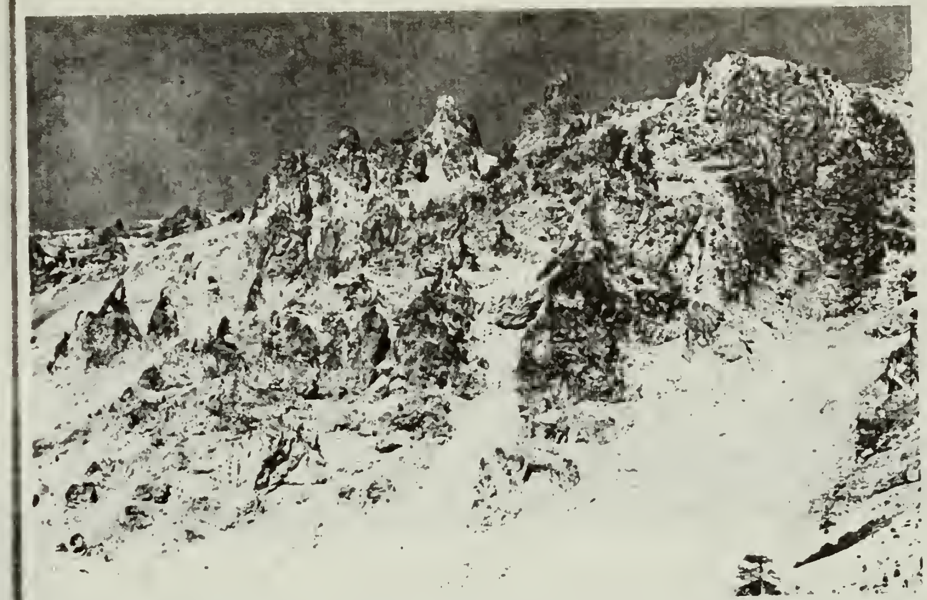
[illegible]

3 EAGLE CRAIGS This 1800
t wall illustrates the
al structure of a composite
e. The dark layers are
esite lava flows and the
ht zones are pyroclastic
osits. Over thirty layers
present.



4-14 DEVIL'S BACKBONE The largest dike exposed in the caldera wall is composed of two sections and extends from lake level to the rim. It represents the pattern of radiating dikes associated with composite cones.

Perhaps the most obvious features to be seen in
e caldera walls are the numerous dikes; magma that
lidifies after filling in cracks. During Mazama's
nstruction, vertical fractures formed, which allowed
gma to move toward the surface. In many cases this
uid rock poured out on the surface as a lava flow but
metimes it became trapped below ground. In any event,
ese fractures were filled with hot rock which even-
ally cooled to create the dikes seen along the walls
day. The most famous of these, called the Devil's
ckbone, is easily seen from many points along Rim
ive, as well as from Sinnott Memorial Overlook below
m Village. The most striking view of this feature,
wever, is from the boat, where the full effect of its
ight and width can be thoroughly appreciated (Picture
14). At the base next to the water, the width is over
m (50 ft) and this portion rises to nearly 160 m
00 ft). It is one of the youngest of the many dikes,



4-15 HILLMAN PEAK Horizontal lava flows are interrupted by jagged intrusions of magma filling the vent area of the Hillman volcano. The collapse disected this flank cone and exposed its internal structure.

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for it cuts across all the older material exposed in the wall, indicating those rocks were present prior to the emplacement of the Devil's Backbone dike. Altogether there are at least twenty dikes exposed in the walls, many occurring along the northern side of the caldera (Map 4-7).

An especially interesting section of the caldera wall can be seen at the west end, under the two peaks named Hillman and The Watchman. If rocks on either side of Hillman Peak are observed, the horizontal layers are readily apparent indicating a typical portion of the wall. Moving in below the peak, however, produces a dramatic change, for the regular layers give way to a dark, massive region with no pattern (Picture 4-15). This represents the internal structure of a flank volcano that had been built on the slope of Mount Mazama. Indeed, there is evidence to suggest that the summit region of Mount Mazama was composed of a series of smaller volcanoes similar to Hillman and The Watchman. When the collapse occurred, approximately half of this flank volcano was caught in that portion which fell away, leaving a cross section of the vent region. Back from the caldera wall along Rim Drive, just north of

[illegible]

[illegible]

[illegible]

[illegible]

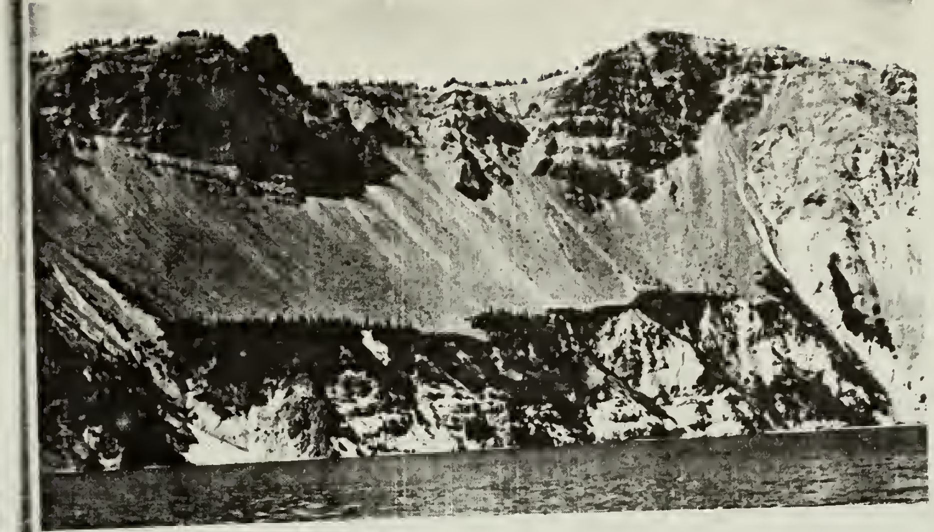
[illegible]

4-16 THE WATCHMAN A dike leads up to the summit and is thought to represent the source of magma which fed the Watchman volcano.

4-17 TALUS SLOPES Pyroclastic zones produce loose debris which slide down the steep caldera walls to form talus slopes. These are among the youngest features in the park, forming since the collapse.

The Watchman turnout, a roadcut has been made through one of the lava flows that originated from the Hillman volcano. A similar situation exists for The Watchman. Rather than such a pronounced vent region, however, a dike can be observed that may have served as the source of fluid rock to feed this volcano (Picture 4-16).

Among the most striking features that can be viewed inside the caldera are the large talus slopes (Picture 4-17). These long, smooth, sandy-looking slopes are really secondary structures, resulting from mass wastage. They have developed by loose debris sliding down the caldera walls, most likely from zones of massive pyroclastic accumulations. These talus slopes and other similar mass wastage features (Picture 4-18), commonly found in mountainous regions, are good illustrations of what happens when slopes become oversteepened and unstable. From a distance they seem to offer easy access down to the lake but are much steeper

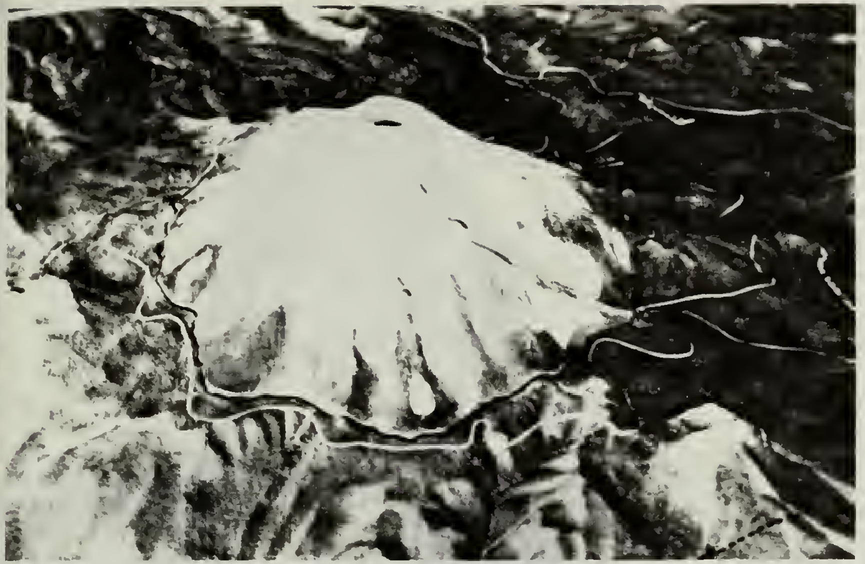


4-18 CHASKI SLIDE This portion of the caldera illustrates mass wastage of a large section of the wall. The part along the lake appears to have moved down as one block from near the caldera rim. Subsequently, talus slopes have formed to cover the scar.

and more difficult to climb than appearances suggest. By far the best route to get down to the lake is the Cleetwood Trail which heads along the north Rim Drive.

The observant visitor may also notice brightly colored areas in several places inside the caldera. These usually occur as shades of yellow, buff, brown, or orange, and often have a weathered appearance, more like an earthy texture than volcanic rock. As eruptions were venting materials from the magma chamber below Mazama, hot, chemically active gases were also being released. As these gases moved upward through fractures, nearby rocks were attacked and partially decomposed, often changing the original minerals to clay-like materials. Minerals in the volcanic rocks containing iron were altered, resulting in color changes from dark green or black to the brightly colored material noted above. This activity is common in volcanic and hydrothermal regions wherever hot gases or water-rich fluids erupt onto the surface.

Most of the evidence for Mazama's construction has been obtained from a careful study of the interior of



4-19 MOUNT MAZAMA A scale model of what Mount Mazama may have looked like can be seen and studied in Sinnott Memorial Overlook at Rim Village. This view is looking toward the west. The nature of the upper portion of the mountain is generalized and the summit region may have been lower, composed of several overlapping cones.

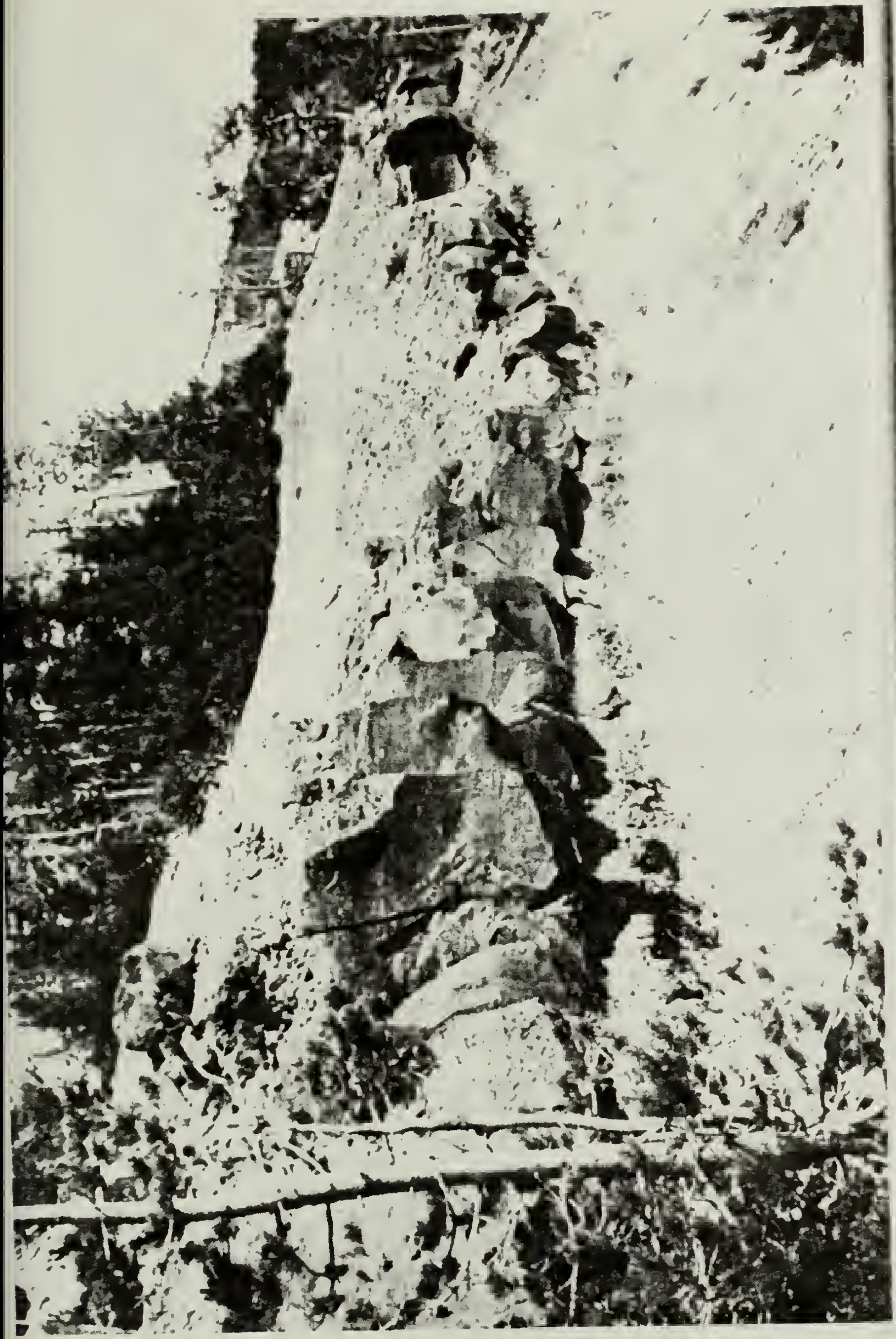
the volcano; the caldera walls. This part of the park has recently contributed important new evidence to the next phase of this geological study. As noted in Chapter One, early geologists discovered that Mount Mazama ultimately collapsed to form the basin that contains Crater Lake. How did this happen? More importantly, Why? In the next chapter the "real" story of Crater Lake will be described as we investigate the final days of Mount Mazama.

Chapter 5

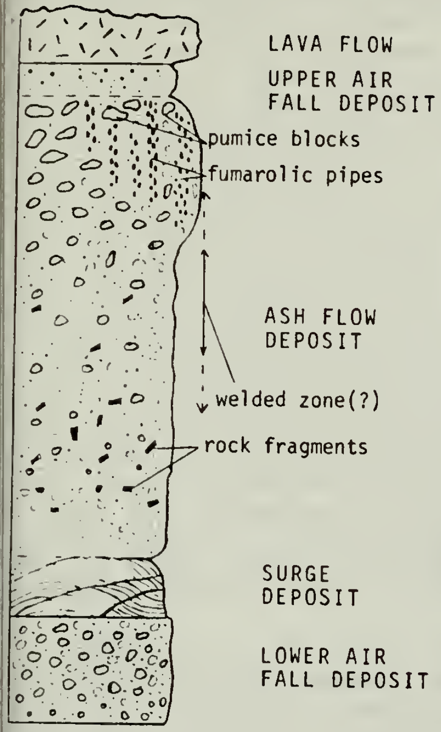
Final Days at Mount Mazama

Mount Mazama's fate has been known for nearly ninety years; since Diller and Patton worked out the basic geological story in the 1890's. Crater Lake marks the location of a large Cascade composite volcano that erupted violently and ultimately collapsed upon itself to form a caldera. Perhaps the most eloquent description of this event was written by Howel Williams in his classic 1942 treatise on the geology of Crater Lake National Park.

Williams' story of the formation of the Crater Lake caldera is based on the large amounts of pumice found in and around the park. He believed that after a rather long rest period, perhaps lasting several hundred years, Mazama's eruptions began anew. Early activity in this renewed series of eruptions was not catastrophic. With time, however, the intensity increased as violent explosions became more frequent. He thought that this trend probably continued until the magma source was exhausted and collapse occurred. The initial weak explosions produced small pumice fragments capable of being transported away from the vent by the wind. As the size of these particles increased, they were not projected as high into the air and the wind



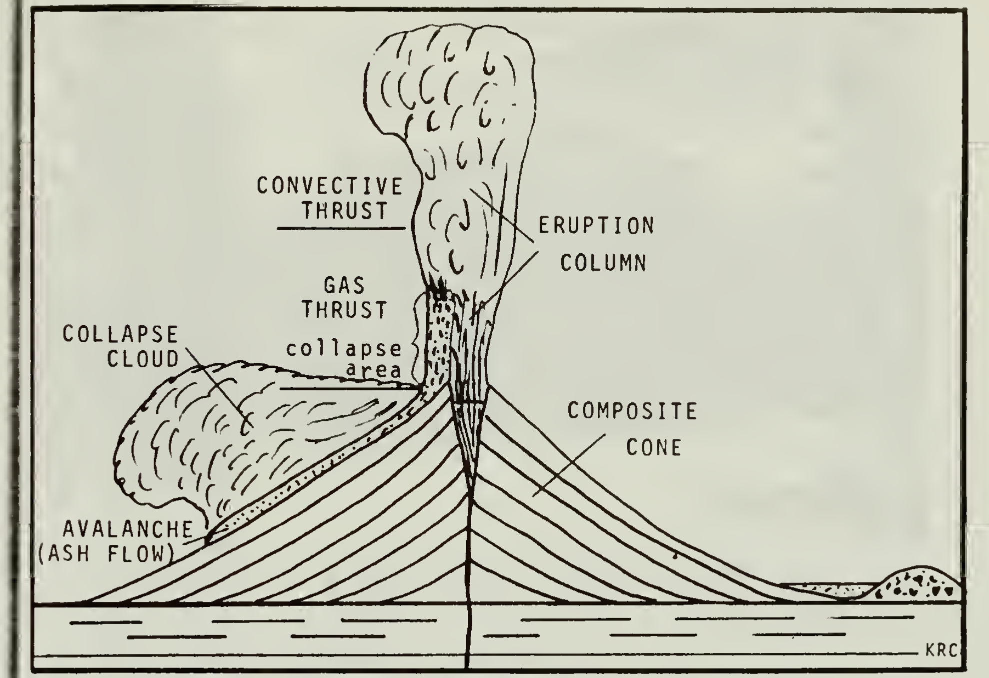
5-1 WELDED ASH ZONE The Wineglass Welded Tuff along the north rim illustrates how hot, ash fall can get. After the ash stopped moving and settled down, the heat built up enough to melt the center part of the deposit. As a result, this feature is often mistaken for a lava flow. (see 5-15)



5-2 IDEAL PYROCLASTIC SECTION This sketch represents a schemactic view of a complete eruption sequence. The lower air fall is deposited first and an upper air fall or lava is last to form. The center part of the ash flow may become so hot that it remelts to form a welded zone that looks like lava (Pictures 5-1 and 5-14).

ould not continue to serve as a transporting agent. ecognition of two distinct types of pumice; small and arge particle deposites, provides evidence for two odes of emplacement. Smaller particles dropping out of he air represent early eruption stages, while the much arger sizes illustrate pumice flows which formed ater. Williams supposed that with this violent series f pumice eruptions, the magma chamber was partially mptied and the upper portion of Mount Mazama collapsed n the resulting void.

The insight Williams displayed is even more amazng in light of recent progress in understanding aldera formation. Much of what will be described in his chapter was not available to him as he pieced the rater Lake story together in the late 1930's. Today, owever, we are the benefactors of a great deal of dditional geological research, theory, and published nformation.



5-3 VIOLENT VOLCANIC ERUPTION Composite volcanoes that experience violent eruptions seem to be the source of ash material shown in the Figure 5-2 sequence. In some cases, these volcanoes also collapse to form calderas. Mount Mazama's climactic eruption was of this type.

Ash Falls and Ash Flows

Williams' account of the collapse of Mount Mazama was made without the benefit of either research or theory of how volcanic pyroclastic material behaves when associated with violent eruptions. Such behavior is extremely important in understanding the caldera-forming event at Crater Lake. Ash ejected during explosive eruptions may assume a number of different behavior patterns, two of which Williams recognized as he carried out his field work in the park. Ash falls and ash flows have become the accepted names for these two types. More recently another variety, known as surge deposits, has been recognized and is thought to develop under certain circumstances.

Although major eruptions which produced large amounts of ash, followed by caldera formation, have never been observed in progress, a number of smaller events are documented. These observations and theoreti-

cal models of how large eruptions behave seem to explain the pyroclastic deposits found in many parts of the world that are related to caldera-forming events. A complete section of a pyroclastic deposit usually contains four (or five in certain cases) distinct zones (Figure 5-2). The first zone, located at the bottom, consists of erupted material deposited by falling from the air. It is coarse-sized but lightweight pumice fragments. This basal air fall is overlain by much finer and more dense particles of pumice, mineral crystals, and rock fragments. This second zone, called a surge deposit, is usually quite thin and shows bedding (distinct layers). Next is the ash flow section, usually the thickest and contains the greatest amount of erupted material. One peculiar feature of ash flows is their inverse depositional pattern, the tendency for larger particles to migrate toward the top of the deposit. This characteristic seems to result from the arger pumice blocks "floating" upward as the ash flow oves down slope and is finally deposited. Additional ir fall ash accumulates slowly on the ash flow to form thin layer of fine material composing the fourth one. In some cases, the final volcanic material to be jected is a lava which caps the entire sequence.

Explanation of this observed sequence can be llustrated by the theoretical model shown in Figure -3. This schematic sketch shows how the ash flow deposits are thought to form from the violent eruption of volcano such as Mount Mazama. The first air fall deposit has already occurred, producing the thin basal one. Escaping gas causes a cloud (gas thrust phase) of as, pumice, rock fragments, and air to rise high above he volcanic vent to a height of several kilometers miles) depending on the pressure. The heat resulting rom the original magma is carried by this cloud and auses further temperature rise of the accompanying air hich reduces the overall cloud density. This results n a convective cloud (convective thrust phase) that ay rise many kilometers (miles) into the atmosphere, ontinuously expanding in the process. A third cloud is ormed that flows down the volcano, also expanding as moves.

This mixture of gas, pumice, rock fragments, and neral crystals represents the upper portion of an ash ow which may have velocities ranging from 14 km/hr mi/hr) to as high as 225 km/hr (140 mi/hr). These ssive pyroclastic flows (ultimately forming the thick h flows shown in Figure 5-2), associated with composite volcanoes, are thought to occur when the gas thrust cloud collapses and the mixture plunges down the flanks of the volcano. It is preceeded by a blast (or surge) of gas and finely suspended pyroclastic debris. The thin surge deposit shown in Figure 5-2, results from this rather mysterious blast. Rapid movement of the subsequent ash flow is due to the hot gases which continue to expand and lift (or push) the solid material being transported down the volcano's flanks. Continuous mixing of ash flow solids, with the large pumice blocks "floating" upward, prevents development of laminar bedding. After the surge layer and ash flow have been deposited, another thin air fall zone gradually accumulates, perhaps by ash settling out from the convective thrust region (Figure 5-3).

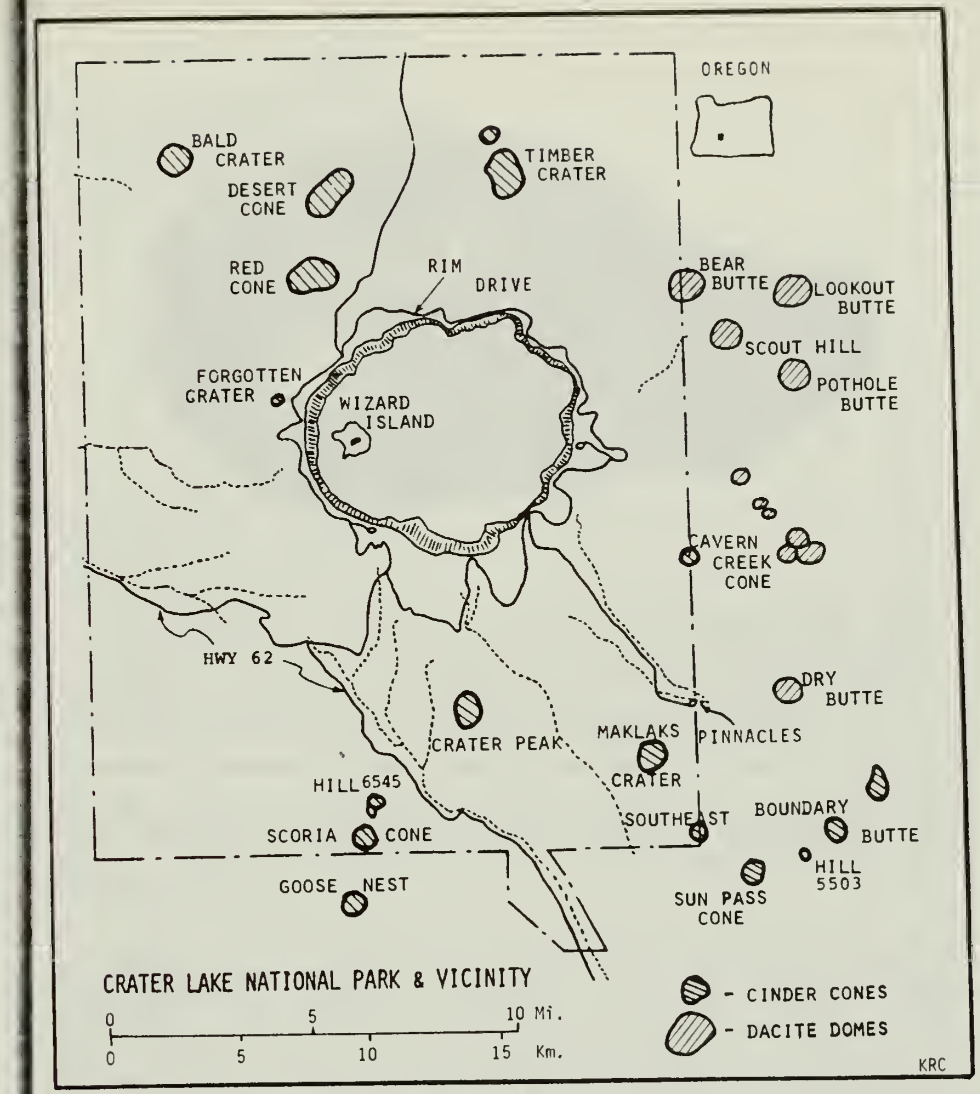
5-4 RED CONE As a medium sized cinder cone, Red Cone is 130 m (430 ft) high and 1 km (2/3 mi) across at its base. Larger cinder cones are up to 200 m (650 ft) high and nearly 1.5 km (1 mi) in diameter (see map 5-5).

Not all zones described in this ideal section can be seen in the exposures at Crater Lake. As we continue to examine the nature of Mount Mazama's final days, some of these ash flow deposits will be described. Understanding the way pyroclastic material is erupted and deposited is the key to interpreting most of the pumice deposits found at Crater Lake.

Cinder Cones and Dacite Domes

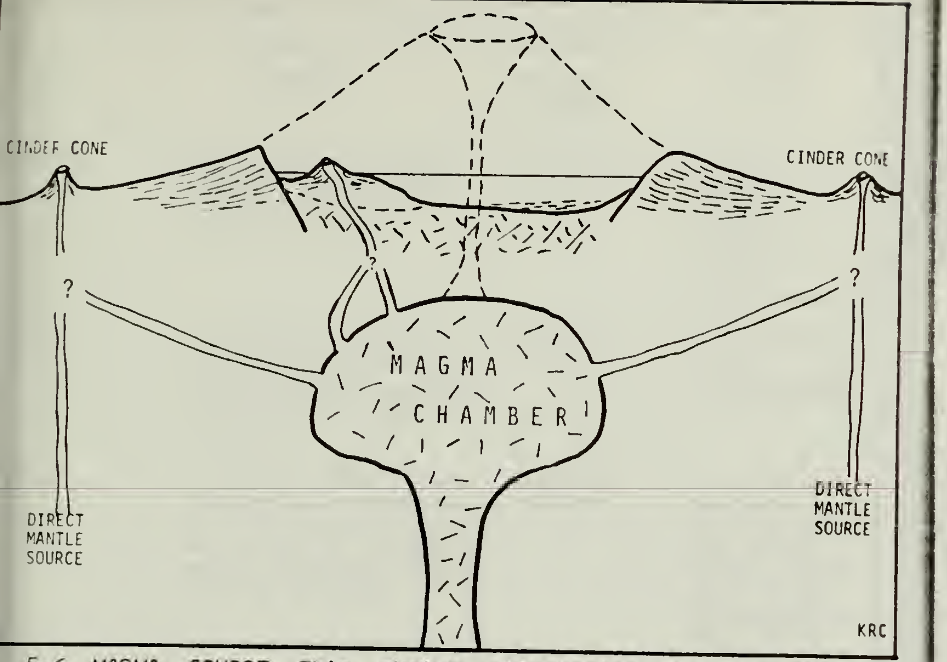
Before continuing with the main story of the massive final eruptions of Mazama ash and its consequence, there is a short side trip of interest. As the landscape of Crater Lake National Park is observed from Rim Drive or other high vantage points along the rim, many small conical hills often attract attention (Picture 5-4). Indeed, there are over twenty of these eye catching humps in and around the park (Map 5-5). Most of these are cinder cones, built by the explosive eruptions of pyroclastic ejecta from a single vent. These features, and the volcanic material which forms them, represent a specific period of volcanic activity in the area. They all are approximately the same age (with the exception of Wizard Island which is younger), being active a short time prior to the final eruptions of Mount Mazama. Although their age has not been precisely established, they are a little older than the final eruptions, but younger than the last major glacial activity in the park. From these observations, the Crater Lake cinder cones appear to be between 8,000 and 15,000 years old.

Before the mid-1970's, these cinder cones were considered to be nothing more than parasites of Mount Mazama. The ejecta which built these small volcanoes was thought to come from the same magma chamber which fed eruptions of the major vent of Mazama. Unlike the andesite lavas which built Mazama, the rocks composing most Crater Lake cinder cones are in the basaltic-andesite range (Table 3). Some geologists continue to support this concept, but others have proposed an alternative explanation. This more recent suggestion views any cinder cone as independent of the major nearby volcano as well as the other local cinder cones. Thus, the magma source must come from some place other than the chamber which produces lava and pyroclastic material for the main vent eruptions (Figure 5-6). So far this question of the nature of cinder cones has not been resolved. It may turn out to be a rather important problem. If the magma source of the cinder cones is deep within the earth's crust or the upper part of the mantle, they could prove to be a "window" to "see" what chemical compositions exist in the mantle. This in turn may indicate what chemical reactions occur deep below the earth's surface. In addition, physical conditions and processes could also be inferred to help understand how the earth's crust and upper mantle behave during magma intrusions.



5-5 CINDER CONES & DACITE DOMES The numerous cinder cones and dacite domes in and around Crater Lake National Park are representative of the hundreds that can be seen in the Cascades. Although the origin of cinder cones may seem obvious, geologists don't agree on the source of magma erupted to form these abundant volcanic features.

Cinder cones at Crater Lake are typical of the hundreds of such volcanic features that occur along the Cascade Range (Figure 2-7). They range in height from less than 30 m (100 ft) to over 200 M (600 ft) and are usually less than 1600 m (1 mi) across at their base.



5-6 MAGMA SOURCE This sketch illustrates two possible sources of the magma erupted in the construction of cinder cones. The solution to this problem may have important implications for understanding where and how magma is formed.

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heir shapes are determined by the slope that loose olcanic ejecta develops as it accumulates, usually orming an angle with the horizontal surface of about) degrees. Lava flows on the upper part of these coria mounds are rare but lava often breaks out at the ase, resulting in flows. Such flows, however, are not xtensive at Crater Lake cinder cones. Crater Peak and orgotten Crater are easily accessible by short hikes o offer a close-up examination of these interesting olcanic features (Appendix Map).

Much less obvious than the cinder cones are small ome-shaped hills that occur along the eastern margin the park (Map 5-5). Although these are about the ame size as some of the smaller cinder cones, they are ormed in a different way. Rather than explosive basal-c lava producing scoria blocks, bombs, and smaller rticles, domes result from rhyolite or dacite being queezed up" toward the surface (Figure 2-7D). Usually ese lavas are too thick to flow and simply pile-up ke a mass of toothpaste. Rapid cooling often results

5-7 OBSIDIAN - RHYOLITE The fascinating glassy black rock called obsidian is really a form of rhyolite or dacite that cooled so fast no crystals could form. Although obsidian does not commonly occur as fluid flows, it is found in lavas erupted on domes and from ring fractures in calderas.

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in a glassy texture which may appear black due to the iron and magnesium being distributed throughout the rock. This is the familiar rock known as obsidian (Picture 5-7).

The relationship of the volcanic activity, that produced the Crater Lake cinder cones and dacite domes with Mazama's final eruptions, is not clear. Some evidence indicates the domes are much older than the cinder cones and thus are not likely to be related to Mazama's large final eruptions. The domes, however, are composed of dacite, the same kind of rock as was ejected during the last explosive period in Mazama's history. As noted above, the source of magma for cinder cones may be completely independent of Mazama's magma chamber.

Formation of the Crater Lake Caldera

Crater Lake and the caldera it occupies seems to display a unique geological setting. Indeed, a common statement applied to the park is, "There is no other place like it in the world." This may be true for many

TABLE 5 TYPES OF CALDERAS

Type	Process	Volume of Ejecta	Example
Krakatoan	collapse of top of large composite cone following explosive eruption of siliceous pumice	less than 100 km^3	Krakatoa Crater Lake, Oregon (10X7 km) Somma-Vesuvius, Italy (4 km diameter)
Katmai	Collapse of volcanic cone summit following drainage of central magma reservoir to feed new eruptions elsewhere	less than 10 km^3	Mount Katmai, Alaska (3 km diameter)
Valles	Floundering along arcuate fractures as a consequence of discharge of colossal volumes of siliceous pumice, independent of pre-existing volcanoes	more than 100 km^3	Valles Caldera New Mexico (20 X 25 km) Long Valley Caldera, Calif. (30 X 17 km) Yellowstone N.P. (48 X 70 km)
Hawaiian	Collapse of the tops of shield volcanoes during late stages of growth; related to subterranean drainage of magma from summit areas to rift zones and flank eruptions	not important	Kilauea caldera Hawaii (4 X 3 km)
Others	Collapse or subsidence due to magma movement associated with shield cones		

spects but from a geological perspective, the Crater ake caldera is not a unique feature. There are dozens, erhaps hundreds, of calderas which have formed in arious volcanic regions around the world. Crater Lake s one of a kind, however, not because it's a caldera, ut because it's such a young, well preserved, and deally-formed. A classic example!

What event or series of events leads to the reation of a caldera? There is no complete answer to his question, but a picture of how these volcanic eatures are formed is being pieced together as more nd more examples are identified and studied. It is omewhat misleading to use Crater Lake as a model for ll calderas because (1) they develop in a wide range of sizes, (2) they exhibit various ages of formation (thus degree of preservation), and (3) they have most likely been formed by several different processes. Table 5 shows several processes by which different types of calderas may develop. Crater Lake falls into the type known as Krakatoan, named from an island in the Sunda Straits between Java and Sumatra, Indonesia.

5-8 THE PINNACLES As the ash flows that filled glacial valleys cooled, hot escaping gases formed fumaroles. The heat welded the loose ash into resistant layers around these vents and today the pinnacles represent fossils of these fumaroles.

Krakatoan type eruptions represent one of the most violent geological events known to occur on the earth. Explosions caused by gas-rich siliceous magma produce great quantities of pumace ejecta, resulting in the ash fall and flow deposits discussed previously. This activity will usually continue for several hours or even days. In relation to our present discussion, evidence from pollen interbedded with Mazama ash suggests activity may have continued intermittently for several years. Judging from Mount Mazama's deposits, great quantities of air fall ash were produced first and then transported away by winds. With time, eruptions became more violent and ash falls gave way to ash flows. Ultimately, these flows assumed the nature of hot, gas-charged clouds rolling down Mazama's slopes at high velocities; the so-called Nuees ardente (glowing avalanche). Theory suggests such features result from the collapse of a gas thrust cloud as discussed above (Figure 5-3). Evidence of this period can be easily seen in the deep valleys eroded into these ash flows

ong Annie Creek, Castle Creek, Sand Creek (Picture
-8) and other streams in the park (Appendix Map).

The next aspect of the Crater Lake story is based
speculation tempered by logic. With the eruption of
rge amounts of magma from Mazama's reservoir, a void
veloped below the volcano. Without adequate support
low, the upper portion of the mountain simply col-
psed to create a caldera. The process resulting in up
1,500 m (5,000 ft) of Mazama's summit falling into
s interior was most likely more complex than just
scribed. There is evidence to suggest that a series
fractures (like the dikes in Chapter 4) developed
ong the northern flank of the volcano. Perhaps these
rved to weaken the northern portion allowing the
llapse to start and progress, intermittently, south-
rd until the summit was consumed. Although the exact
chanism is unknown, it required only a relatively
ort period of time. Based on similar geological situ-
ions in other areas of the world and legends of local
tive Americans, the duration of collapse can be
asured in days, or weeks, if not in hours.

uses of the Final (Climactic) Eruption

As previously stated, Crater Lake is considered
e of the classic examples of a caldera. A good deal
attention has been focused on the process of caldera
rmation using Crater Lake and several other calderas
models. Only recently, however, has the question of
y calderas form, been addressed by geologists working
volcanic regions. And although a unique answer is
t available, several theoretical solutions have been
ggested to explain the violent activity associated
th the creation of a caldera.

The key to explaining massive eruptions of silica-
ch ejecta is understanding how these become so highly
s charged. Magmas with high SiO_2 composition can
commodate several percent volatiles (mostly water
por) in solution. Under high pressure, these gases
ssolve in the magma more easily but a reduction of
essure results in exsolution; the escape of gas from
liquid. A familiar example of this process is any
rbonated soft drink. As soon as the top is removed,
leasing the pressure, escaping CO_2 gas fizzes out
xsolution). High temperatures have just the opposite
fect; as the temperature increases volatiles are
rced out of the liquid. Again, warm or hot soft
inks are considerably more "explosive" than those
illed before opening. This phenomena of dissolved gases in magmas provides the basis for understanding massive volcanic explosive-collapse features such as developed at Crater Lake.

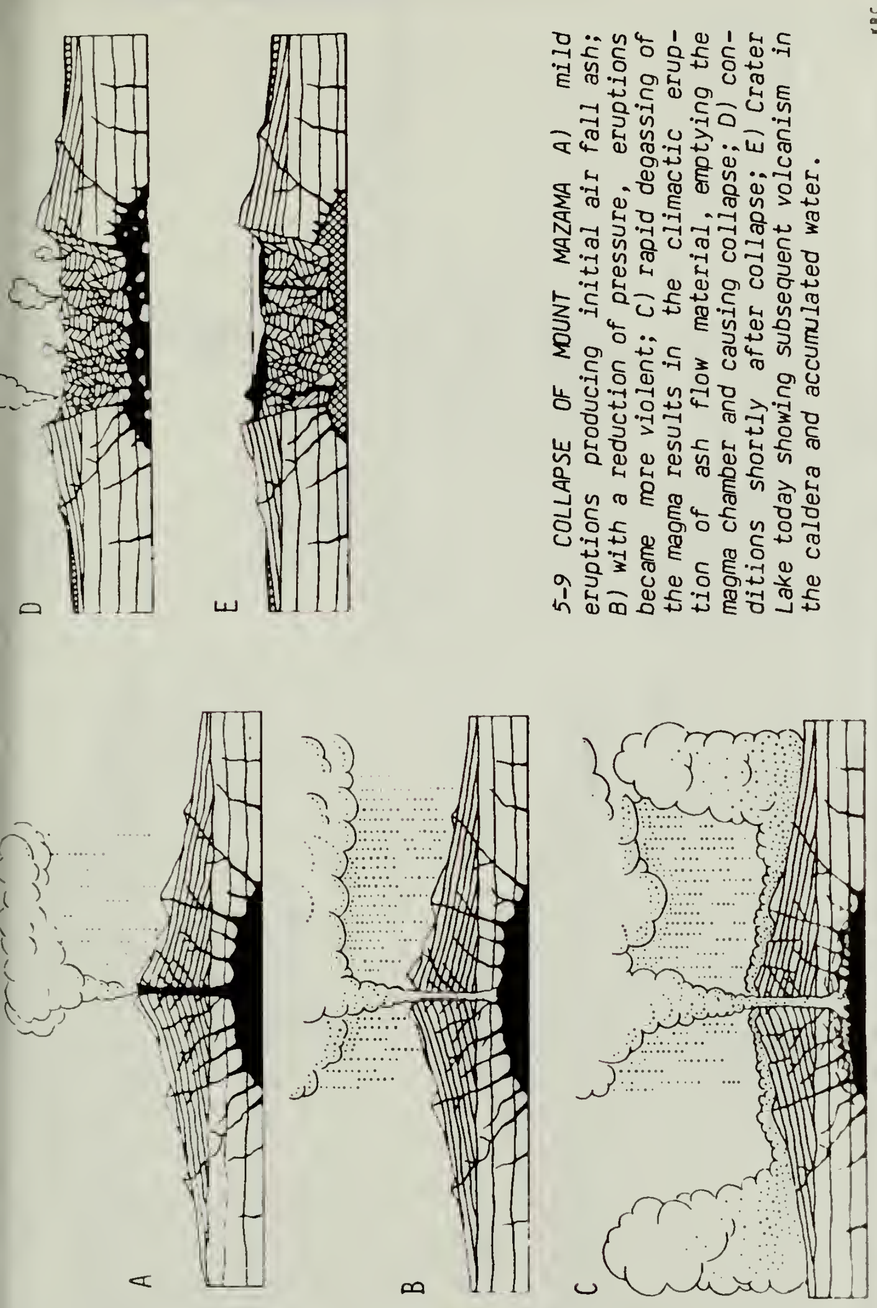
TABLE 6 COMPARISON OF CLIMACTIC ASH VOLUME AND MISSING MAZAMA SUMMIT

MATERIAL	VOLUME		CORRECTED VOLUME	
MISSING SUMMIT MATERIAL	62 km^3	(15 mi^3)	62 km^3	(15 mi^3)
ASH MATERIAL				
Preliminary ash falls	29 - 37 km^3	(7 - 9 mi^3)		
Main ash flows	25 - 33 km^3	(6 - 8 mi^3)		
Final ash falls	1 km^3	(0.25 mi^3)		
TOTAL	55 - 71 km^3*	(13.3 - 17.3 mi^3)*	42 km^3	(10 mi^3)
		DIFFERENCE	20 km^3	(5 mi^3)

* Mapping of the ash ejecta produces a volume far too large because the ash expanded greatly upon leaving the magma chamber. In order to estimate the actual volume it occupied as magma, the present totals must be multiplied by 0.67. (see section on distribution of Mazama ash for another interpretation).

Although the exact mechanism is unknown, two models have been proposed to explain these violent events. The older explanation is the least complicated. It's based on an accounting of the amount of material ejected during the climactic eruption, as compared to the amount of Mount Mazama which collapsed into the partially emptied magma chamber. This balance sheet is computed by mapping all the ash fall and ash flow ejecta to calculate their total volume. Next, an estimate is made of how much Mazama rock material disappeared by speculating on the size of the original volcano. These figures are shown in Table 6. Such comparisons suggest that about 1/3 more summit volume was engulfed than can be accounted for in the existing ash deposits. This information is the major evidence supporting a model commonly known as magma withdrawal.

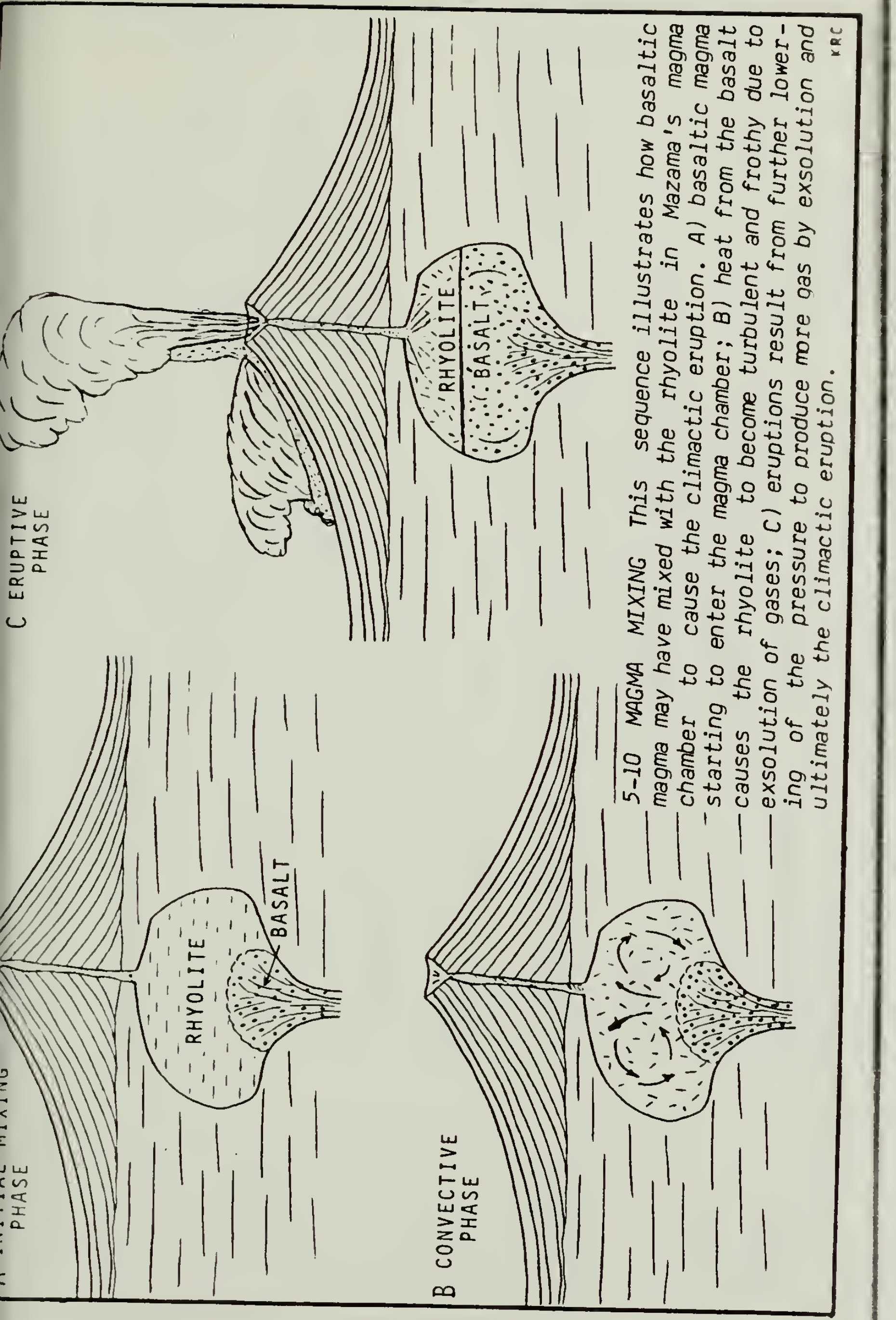
Since more of the magma chamber was emptied to allow the summit collapse, than can be attributed to the ejected ash deposits, some magma must be removed by another mechanism. The method usually proposed is withdrawal of magma back down into the earth's interior or to another site experiencing surface activity. In the



5-9 COLLAPSE OF MOUNT MAZAMA A) mild eruptions producing initial air fall ash; B) with a reduction of pressure, eruptions became more violent; C) rapid degassing of the magma results in the climactic eruption of ash flow material, emptying the magma chamber and causing collapse; D) conditions shortly after collapse; E) Crater Lake today showing subsequent volcanism in the caldera and accumulated water.

case of Crater Lake, there is no evidence to confirm such movements of magma and thus the model is partially built on an assumption. The initial effect of magma withdrawal is a reduction of pressure in the magma chamber. This may result in a sudden increase in temperature along with rapid exsolution of volatiles. Such a combination could cause the magma to become turbulent and eventually frothy. A series of explosions, caused by the expanding gases, could then produce large amounts of air fall ash. Fractures developed in the flanks of Mount Mazama, with the highly energetic magma moving into these, which further reduced the pressure. Exsolving gas created the energy to drive the frothy liquid upward and, like a soft drink when its top is removed, the magma expanded rapidly. Cooling resulted due to this rapid expansion so that the ejected magma was solidified quickly to become a rather porous, glassy solid with a sponge-like texture. Gas continued to exsolve even as these ash flows raced down the slopes of Mazama. This resulted in a bouyancy which permitted the ash to travel for many kilometers, even on level ground. As this process was occurring, or very soon afterwards, Mazama's summit settled into the space previously occupied by the escaping magma. Figure 5-9 illustrates this sequence of events.

A somewhat more complex model goes under the name of magma mixing. Basaltic magma, generated in the earth's mantle, moves upward into the lower crust and provides a heat source to partially melt the rocks that occur there. Because the temperature of basaltic magma ranges between 1,100°and 1,300° C (2,000° - 2,375° F), lower crustal rocks, which are composed of minerals that melt at lower temperatures, will readily start melting. The first liquid to form from this melting of the lower crustal rocks is rich in SiO_2 and has a composition similar to rhyolite or dacite. These accumlate and slowly migrate toward the surface as large blobs of diapirs. If, at some later time, this mass of rhyolite magma encounters a batch of basaltic magma (like the one that furnished heat to produce the rhyolite originally), mixing will likely occur. With the hotter basalt again providing heat, both liquids will become turbulent and mix. If thorough mixing occurs with approximately equal amounts of basalt and rhyolite, the resulting magma should have the composition of andesite. In Chapter Four it was noted that most of the lava flows associated with the construction of Mount Mazama are andesites. The same conclusion can be drawn for all the Cascade composite volcanoes. The production of andesite is a topic of much debate among geologists.



5-10 MAGMA MIXING This sequence illustrates how basaltic magma may have mixed with the rhyolite in Mazama's magma chamber to cause the climactic eruption. A) basaltic magma starting to enter the magma chamber; B) heat from the basalt causes the rhyolite to become turbulent and frothy due to exsolution of gases; C) eruptions result from further lowering of the pressure to produce more gas by exsolution and ultimately the climactic eruption.

Magma mixing, however, provides a method strongly favored by some experts.

Mazama's magma chamber then may have contained rhyolite, which was periodically mixed with basalt, to produce the andesite erupted as lava. In this way, a large composite cone gradually rose to a height of perhaps 3,600 meters (12,000 ft) above sea level. There were, of course, occasional eruptions of pyroclastic ejecta that represented more explosive periods of Mazama's history. Some time prior to the collapse, the rhyolitic magma had established a shallow chamber beneath Mazama. As rising basalt encountered this gas-rich rhyolite, the rhyolite was quickly superheated causing strong turbulence and degassing in the magama chamber. Several explosive episodes of pyroclastic ash fall occurred in response to this early mixing. Eventually, however, the escape route was plugged and temperatures increased causing further exsolution of the volatiles. Swelling of Mazama may have occurred as additional basalt was injected into the rhyolite magma chamber. When the stress below became too great, a series of fractures developed allowing the confined magma to escape in one grand and final rush. At this point the magma mixing model follows the same sequence of events as described for the magma withdrawal theory. Figure 5-10 illustrates how magma mixing might occur to create the Crater Lake caldera.

Both of these suggestions appear reasonable as an explanation for the Crater Lake caldera but it must be noted that they are "models." There is a difference between reality and a model which seems to fit the evidence and provide a logical explanation of events. Do not confuse them.

Sequence of Climactic Events

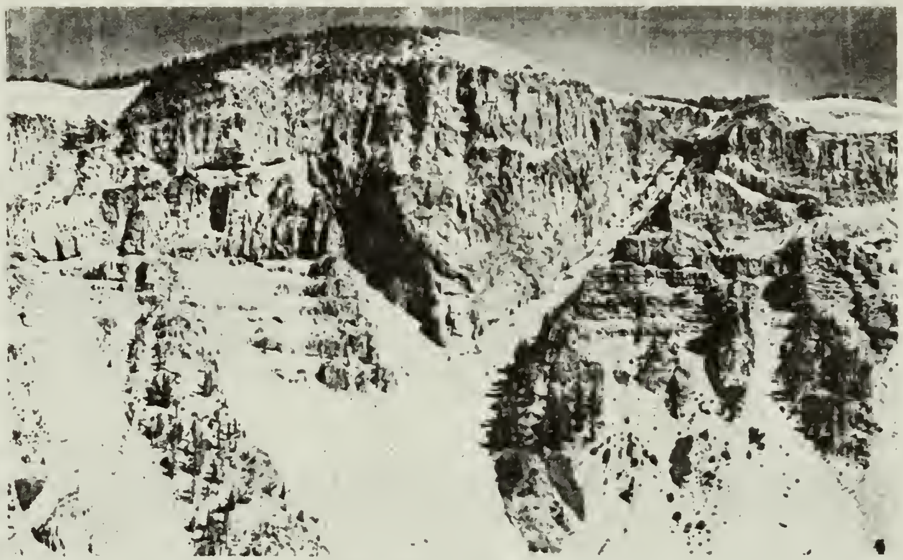
Since Williams conclusively demonstrated the collapse of Mount Mazama, the next logical question concerns the final events leading up to the collapse? Although Williams and geologists who followed him have made various proposals, it remained for Charles Bacon to work out the details in the early 1980's. This section describes Bacon's interpretations.These are based on both his field work and that of other investigators, who have contributed to a more complete understanding of Crater Lake geology.

TABLE 7 ERUPTIVE HISTORY OF MOUNT MAZAMA

Time (YBP)*	Event	Nature of Ejecta	
6,840	POST-CALDERA VOLCANISM	Cinder Cones and Lava Flows in Caldera	
		Final Fallout	Multiple Vents
6,840 ±30	CLIMACTIC ERUPTION	Main Pyroclastic Flows	
		Wineglass Welded Tuff	Single Vent
		Climactic Pumice Fall	
	CLEETWOOD FLOW	Dacite Flow (Still Hot at 6,840 YBP)	
		Local Pumice Fall	
	GROUSE HILL FLOW	Dacite Flow (Local Pumice Fall?)	
7,015 ±45	LLAO ERUPTION	Llao Rock Dacite Flow	Same Vent
		Lower Pumice Fall	
	FORGOTTEN CRATER	Basaltic-Andesite (Mixed Dacite and Andesite Scoria)	
10,000	REDCLOUD CLIFF	Dacite/Rhyolite (Tephra and Lava Flows)	
Mostly 50,000	ANDESITE STRATOCONES	Andesite Flows with Minor Silicic Products	

*YBP = Years Before Present

after Bacon, 1981



5-11 REDCOUD CLIFF The massive V-shaped dacite lava flow which is exposed in the caldera wall fills an explosion crater. Since this lava was extremely viscous, it did not flow easily.

An outline of Mazama's climactic events is presented in Table 7. The volcanic behavior of Mount Mazama changed sometime before ten thousand years ago. Prior to this, the dominant volcanic activity consisted of andesite lava flows with minor amounts of silicic (dacite and rhyolite) material being ejected. Most of the exposures in the caldera walls surrounding the lake exhibit this long history of andesite eruptions.

The massive lava flow exposed on the eastern caldera wall is called Redcloud Cliff and represents this change of behavior noted above (Picture 5-11). It sets a pattern, that was followed by several of the climactic eruption features, which occurred a few thousand years later. A vent was blown in the flank of Mazama by the gas charged dacite magma. This magma was ejected as tephra until the gas pressure subsided. At this point, thick dacite lava flowed, filling the vent and forming the dome-like structure represented today by Redcloud Cliff. Mazama became quiet following the outburst of Redcloud dacite allowing gas pressure to begin building once more.

5-12 *FORGOTTEN CRATER The conduit which formed this cinder cone may have been close enough to draw off a little magma from Mazama's chamber.*

5-13 *MIXED LAVA Rhyolite in this lava flow (light bands) may represent magma from Mazama's chamber which mixed with the basaltic material that built Forgotten Crater.*

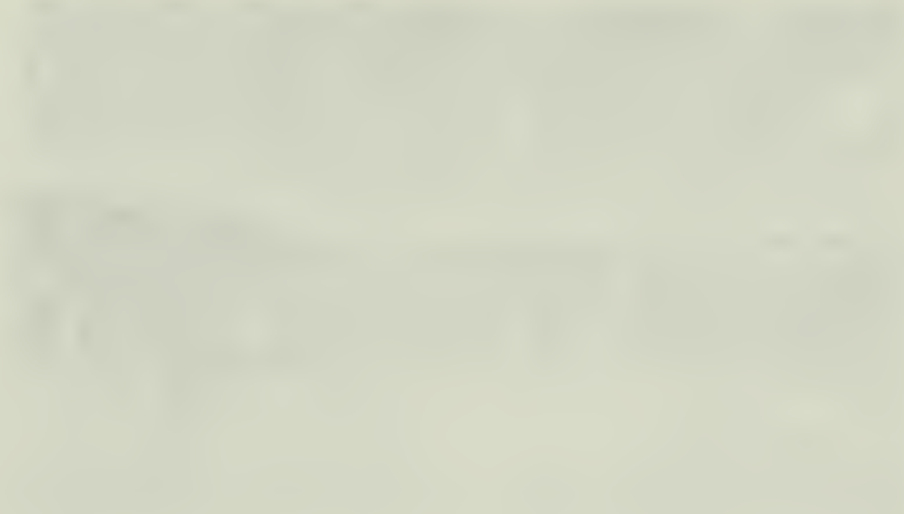
Sometime during this period, while gas was reharging the magma chamber, Forgotton Crater (Picture -12) began erupting. Judging from the composition of he material (basaltic andesite) produced, it appears o be tapping a completely separate magma source. Since ts conduit to the surface was so close to Mazama's agma chamber, it's possible that a small leak developd. As a result, some of the silicic magma from azama's main chamber escaped and was erupted along ith the basaltic andesite which built Forgotten rater. Today evidence of this leak is found as abunant pieces of mixed scoria (Picture 5-13) associated ith Forgotten Crater pyroclastic deposits.

5-14 *CLEETWOOD FLOW The eruption of lava from this vent occured just prior to the collapse and was still hot enough to partially flow back into the caldera as the collapse developed.*

The next major event occurred about seven thousand ears ago. By that time, the magma chamber below Mazama ad replenished its gas content and pressure. The Llao ruption developed, proceeding much like the Redcloud liff event described above. Following the initial ruption, which formed the Llao vent and produced ephra deposits, the massive Llao dacite flow was emplaced (Picture 4-8). At this point, geologists ability to make accurate time determinations improves dramatically. Carbon remains of plants,which were buried in the Llao tephra, allow this event to be dated at 7,015 ±45 years using the radiocarbon technique discussed later in this chapter.

Grouse Hill, a second large dacite flow, was formed shortly after the Llao rock event. It lies away from the caldera, however, and thus is not exposed as well as the previous two dacite flows. Although Grouse Hill appears to be similar to both the Llao Rock and Redcloud Cliff features, it may not have produced a significant tephra phase (see Appendix Map).

Just a little over sixty-eight hundred years ago, Mazama had worked itself into position for the climactic eruption. This final sequence probably began with a fourth explosion vent much like Llao Rock and Redcloud Cliff. The Cleetwood eruption also produced an initial tephra phase followed by a thick dacite flow (Picture 5-14). It almost appears as if this vent triggered the climactic eruption which followed in a brief period of time. Indeed, the time between these two events was so



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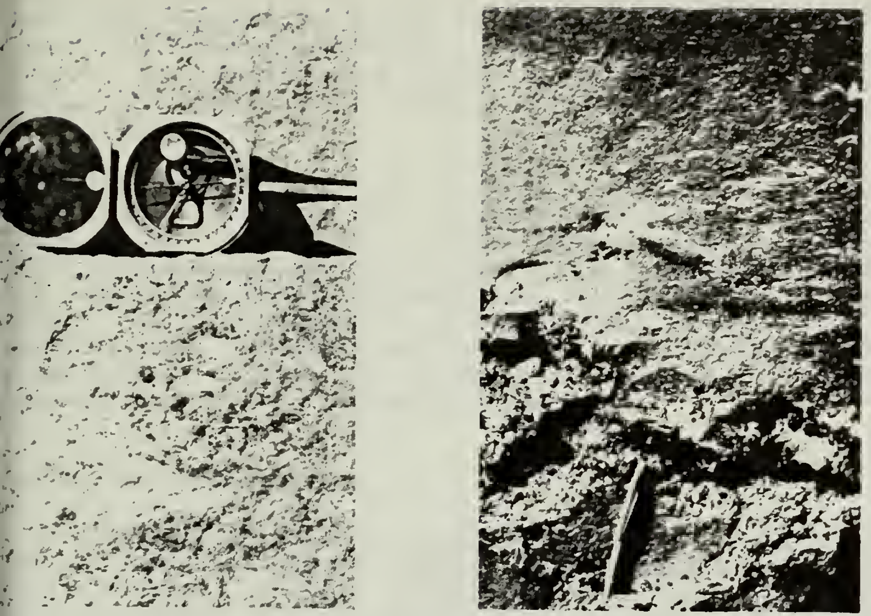


5-15 FLATTENED PUMICE - OBSIDIAN STREAKS This ash, which formed the Wineglass Welded Tuff, was so hot upon eruption that it caused the large pumice blocks to partially collapse (A) or reform into obsidian layers(B).

ort that the Cleetwood flow had not completely cooled fore climactic eruptive ejecta covered it over.

The first phase of the climactic event consisted pumice eruptions from a single vent located where e deepest part of the lake now exists. With the rong gas pressure pushing this pumice out vertically d the prevailing wind from the southwest, great anities of Mazama ash were carried toward the north- st. Today, as described in the next section, this ash n be found over a great region of the northwestern ited States and into Canada.

Toward the end of this eruption, portions of the ected material were extremely hot and fell close to e vent. Once any movement had ceased, the high temp- atures caused partial melting in the center of this phra deposit. Large pumice blocks collapsed to form rizontal fragments or thin black obsidian streaks icture 5-15). Such a condition is said to produce lding of the deposit. This feature, called the Wine- ass Welded Tuff, developed only in the low portions of Mazama's northern and eastern slopes. Today, where it is present, the Wineglass Welded Tuff makes an easily recognized zone near the top of the caldera wall.

Following deposition of the Wineglass Welded Tuff, volcanic activity changed from a single vent to multiple vents. It is thought that a significant amount of magma was ejected from the magma chamber, during the first phase of the climactic eruption, to initiate collaspe of the summit area. As subsidence occurred, new fractures were formed that nearly encircled the volcano. These vents provided an escape route for the main pyroclastic flows. They must have "boiled-out" much like the soda pop analogy used earlier in this chapter. As the confining pressure on the magma was released, the dissolved gases quickly exsolved causing an explosive expansion. This drove the magma out through the fracture vents which were forming as the summit settled into the interior. Massive pyroclastic flows poured down Mazama's slopes in all directions.

But why was the fluid rock, which was stored in the magma chamber, erupted as pyroclastic flows and not lava? It has to do with the rapid expansion produced by the gases. The most likely explanation suggests that this magma was close to its freezing temperature when the summit collapse began. The magma was driven out through fractures, causing it to cool, by the expanding gases exploding through this thick liquid rock. Consequently, this reduction in temperature caused the magma to freeze almost immediately. Gases continued pushing this solidifying magma out of the chamber as fragmental pumice debris. Even as it flowed away, gases continued to exsolve from the solid particles providing a bouyancy or "cushion" of gases, that carried and pushed the flowing mass down the valleys surrounding Mazama. Finally, some fine ash was blown upward into the air during this final phase of the climactic eruption. Gradually, it settled down on the surface forming the thin final fallout zone that can be found on top of everything else.

When the main pyroclastic flows stopped moving, the stream valleys were filled to depths up to several hundred feet. Gases continued to exsolve from the pyroclastic material and percolate toward the surface through channel-ways called fumaroles. Fine ash in the fumaroles was removed by the gas, leaving only coarse fragments in these vents. Minor welding occurred along these vertical channels because the gas was still hot.

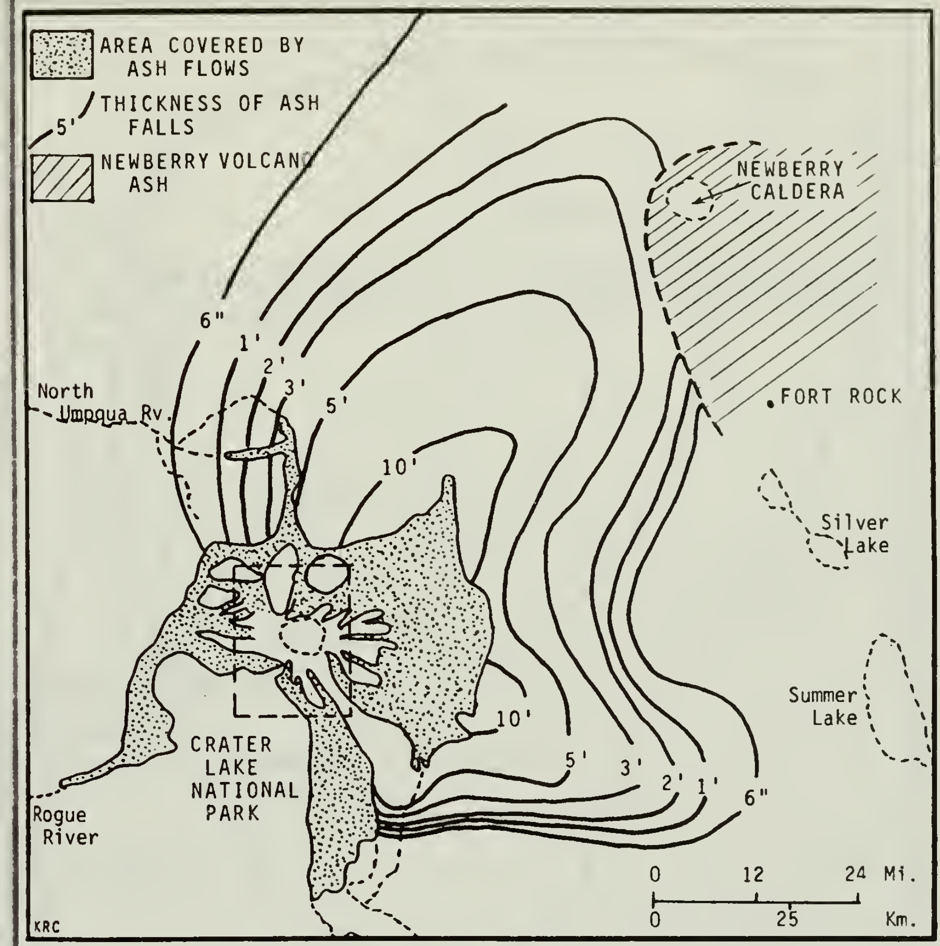
Today, portions of the thick main pyroclastic flows have been removed by stream erosion over the past 6,800 years. In favorable locations, such as Wheeler Creek Canyon and Annie Creek Canyon, remains of these fumaroles, now standing as resistant pinnacles, can easily be observed.

Thus, the Crater Lake caldera came into existence, following this brief but violent activity, that we refer to as the climactic event. Indeed, from a geological perspective, it was instantaneous. In Chapter Six the story of what followed the collapse will be continued. For the balance of this chapter, however, let's examine some of the ramifications, resulting from the great amount of pyroclastic material ejected by Mount Mazama, during this climactic event.

Distribution of Mazama Ash

As noted in Table 6, large amounts of ash were deposited as ash flows during the climactic eruption. Several other Cascade volcanoes have also produced major amounts of air fall ash during explosive eruptions in recent geological time. One may wonder how Mazama tephra can be distinguished from that of Mount St. Helens, Mount Rainier, Newberry Crater, or others. There are several methods employed to accomplish this task. The amounts of specific minerals and the refractive index of the pumice glass are two important techniques. When the tiny mineral crystals found in a certain tephra are identified and counted, their percentage remains constant regardless of where the ash is found. The same condition occurs for the refractive index of glassy portions of the pumice. In fact, the variation, in either mineral percentages or refractive index over the region where Mazama ash is found, is no greater than in a single fragment of pumice. And, of course, the values of these characteristics are different for tephra produced by other volcanoes. As a result, a fragment of tephra found anywhere in the Pacific Northwest can be examined to learn if it originated during the climactic eruption at Mount Mazama.

One of the features of Williams' study of Crater Lake in the late 1930's, was a detailed mapping of Mazama ash. Its thickness was measured and plotted on a map, for many locations in central Oregon. By connecting points of equal thickness, an estimate of the total volume could be calculated. Map 5-16 illustrates this method for any thickness greater than 15 cm (6 in), the thinnest layer mapped by Williams. Calculations of the volume of all the climactic eruptive material resulted in an estimate of 44.5 km^3 (11 mi^3) as noted in Table 8. The amount of missing Mazama summit material was placed at 71 km^3 (17 mi^3). After correcting the ash value to represent its volume as magma prior to eruption, a 46 km^3 (10.5 mi^3) descrepancy existed. Thus, Williams proposed the magma withdrawal model discussed above. Nearly thirty years later, after additonal study



5-16 DISTRIBUTION OF MAZAMA ASH This map shows Williams' original determination of the area covered by ash from Mount Mazama. Note how the ash flows followed the glacial valleys to the south, southwest and north.

TABLE 8 VOLUME ESTIMATES OF ASH DEPOSITS FROM CLIMACTIC ERUPTION

Type	(1) Williams - 1942	(2) Williams & Goles - 1968	(3) Lidstrom - 1972
Preliminary Ash Falls (Tephra)	14.5 Km^3 (3.5 Mi^3)	33 Km^3 (8 mi^3)	73 Km^3 (17.75 Mi^3)
Main Ash Flows	29 Km^3 (7Mi^3)	29 Km^3 (7 Mi^3)	29 Km^3 (7. Mi^3)
Final Ash Falls (Tephra)	1 Km^3 (0.25 Mi^3)	1 Km^3 (0.25 Mi^3)	1 Km^3 (0.25 Mi^3)
Totals	44.5 Km^3 (10.75 Mi^3)	63 Km^3 (15.25 Mi^3)	103 Km^3 (25 Mi^3)
Corrected to Magma Volume	25.3 Km^3 (6.5 Mi^3)	37.3 Km^3 (9 Mi^3)	61 Km^3 (14.8 Mi^3)
Volume of Missing Summit	71 Km^3 (17 Mi^3)	62 Km^3 (15 Mi^3)	62 Km^3 (15 Mi^3)

Note: Data presented in this table has been simplified for ease in understanding. Different methods were used in calculations of columns 2 and 3, so the published data is not directly comparable.

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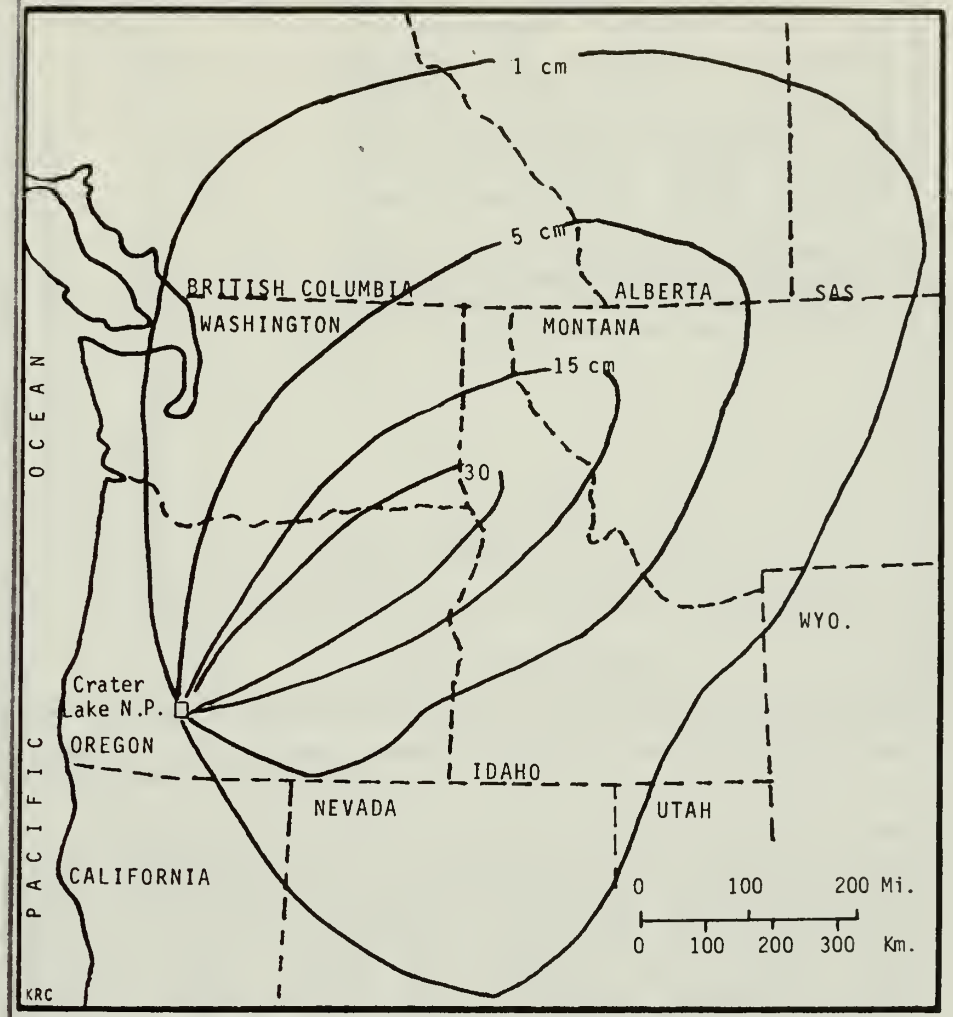


5-17 NEW ESTIMATE OF MAZAMA ASH DISTRIBUTION A much greater area of Mazama air fall ash was mapped by Lidstrom using new methods for estimating the thinner regions of ash deposits. From this map it appears that ash was carried 1400 km (800 mi) from Crater Lake to the northeast.

of the tephra volume, a new set of figures was proposed (column 2, Table 8). This 1968 study allowed more tephra to be included and reduced the volume of Mazama's summit that had disappeared. The difference, however, between the two sets of values was still large, some 24 km^3 (6 mi^3). Magma withdrawal continued to serve as the mechanism for explaining how the Crater Lake Caldera was created.

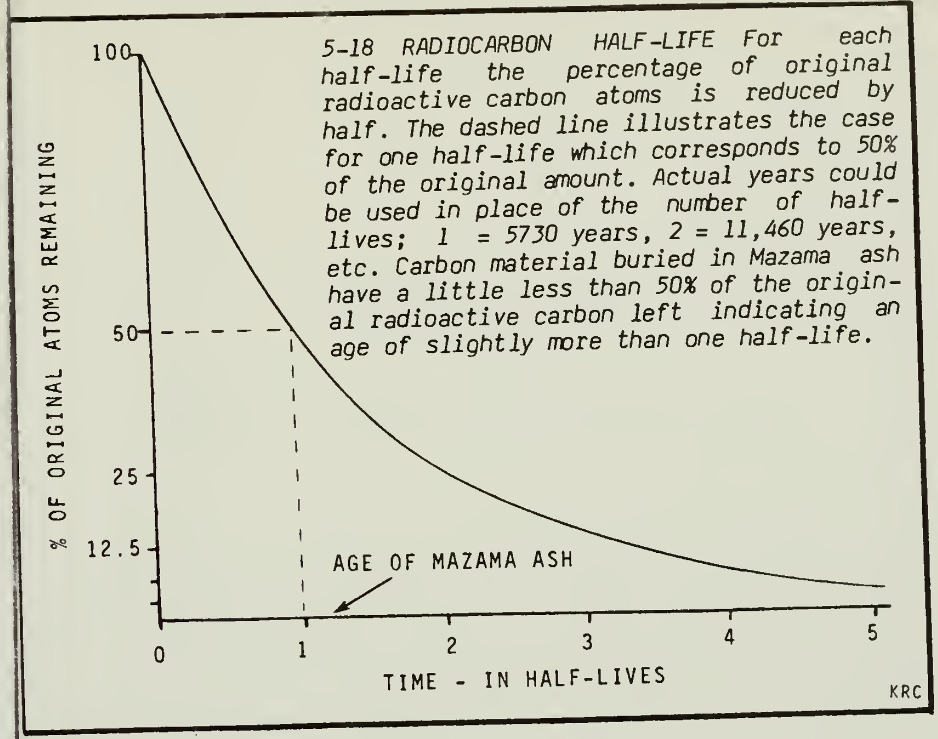
More recently, using additonal data and another echnique to estimate total tephra, a third calculation as been made (column 3, Table 8). Map 5-17 displays he equal thickness lines used as a basis for this stimate. When missing Mazama summit and ash volume are ompared in this study, the values are nearly equal ndicating that enough material had erupted to allow ollapse. It is not necessary to assume that any magma as withdrawn from below Mount Mazama, and as a conequence, the model based on magma removal to allow ollapse is also unnecessary. Most geologists, however, end to ignore this study and prefer to use the 1968 alues when discussing the formation of the Crater Lake aldera.

ating the Crater Lake Caldera

In previous discussions, the time of caldera foration was given as about 6,800 years ago. The methods sed to establish this date makes one of the most ascinating studies associated with Crater Lake geolgy.. After considering several ways to estimate the ime of collapse, Williams concluded that it must have ccurred between 4,000 and 7,000 years ago. He chose ,000 years as the approximate age of the caldera. More ecently, however, a more precise tool for dating young eologic events has been developed; radiocarbon dating.

Certain carbon atoms, that are unstable, disinterate to form nitrogen which is stable. The conversion rom carbon to nitrogen,for a specific atom, is not redictable but for a large number of atoms, the time equired for half of them to be converted is known. his rate is expressed as its half-life and represents he time for half of any given amount of radioactive arbon to convert to nitrogen. After one half-life, alf the original radioactive carbon has changed to itrogen, in two half-lives, three quarters has conerted, in three half-lives, seven eighths, and so on. his is illustrated in Figure 5-18.

Since carbon is abundant in all living matter, and certain portion is radioactive, all organisms contain constant balance of radioactive carbon. When death ccurs, no new carbon is being added so any radioactive arbon in the organism starts to change to nitrogen. By etermining how much of the orginal radioactive carbon emains at any time, the length of time since death can e measured. One half-life of radioactive carbon is bout 5,730 years, close to the age of the Crater Lake caldera. It almost seems that this dating method was custom made for use here.



5-18 RADIOCARBON HALF-LIFE For each half-life the percentage of original radioactive carbon atoms is reduced by half. The dashed line illustrates the case for one half-life which corresponds to 50% of the original amount. Actual years could be used in place of the number of half-lives; 1 = 5730 years, 2 = 11,460 years, etc. Carbon material buried in Mazama ash have a little less than 50% of the original radioactive carbon left indicating an age of slightly more than one half-life.

Because the climactic eruption and resulting ash flows occurred over a brief period of time, anything killed by burial in ash would show a radiocarbon age equal to the age of Mazama's collapse. Prior to burial under the ash flows and air falls, the landscape surrounding Mount Mazama was forested. In most cases, the trees covered during the climactic eruption were killed, experienced ordinary organic decay, and soon disappeared. Under certain circumstances, however, trees were changed to charcoal and thus preserved. This happened when the ash flows were hot. Since trees buried in this process could not burn in the ordinary way, due to lack of oxygen, the volatiles in the wood were driven off as gases. This left only the carbon behind as charcoal. Conversion to charcoal did not affect the radioactive carbon and it began to change to nitrogen. When such a tree is found today, buried in Mount Mazama ash, samples can be dated (Picture 5-19). Several dates determined in this way fall in the vicinity of 7,000 years. Recent determinations produce

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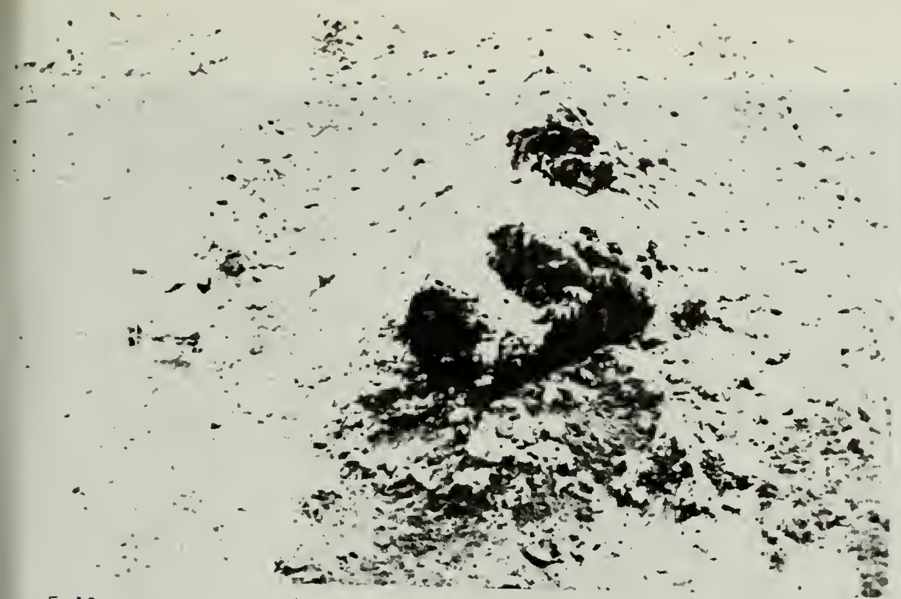
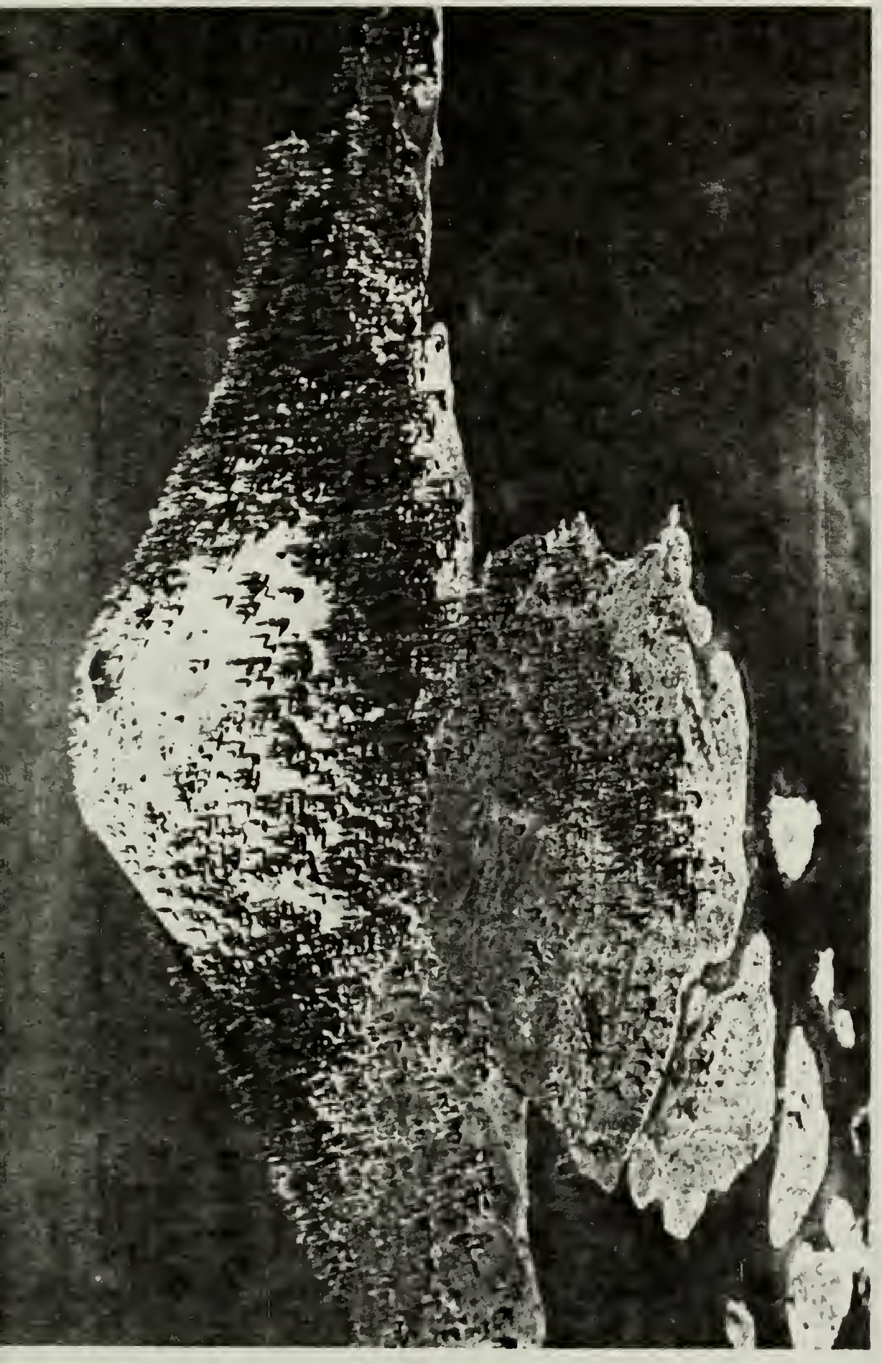


5-19 CHARCOAL LOG This end-on view of a log buried in Mazama ash is typical of many that can be seen in the Umpqua River valley northwest of the park. Notice the lack of any bedding which is characteristic of ash flows.

date of about 6,800 years and this has been taken as he age of the Crater Lake caldera.

With the climactic eruption, dispersal of huge uantities of ash, and the ultimate collapse, Crater ake tells a fascinating story of Mount Mazama. The vidence in the form of the caldera and massive accumu- ations of ash leave little doubt of what happened. But his is not the end of the story. A large part of what e see today in the park has developed since those few ours, days, or weeks of violent volcanic activity hich destroyed Mount Mazama. And although it may seem nticlimatic at this point, recent geological studies ave made this part of the story quite exciting. It ontinues in Chapter Six.



Chapter 6

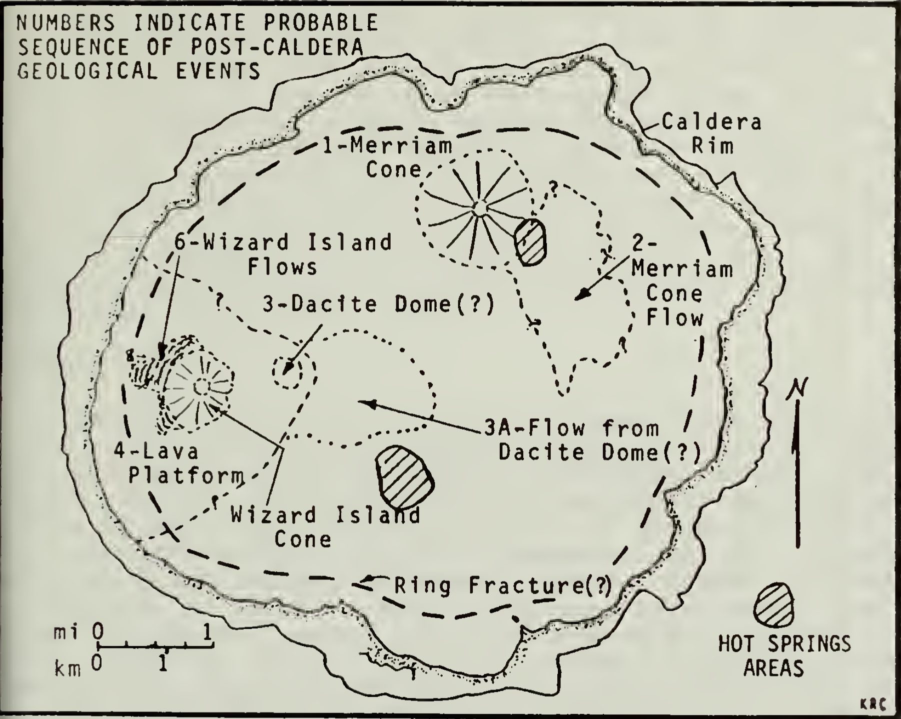
After Mount Mazama

With the collapse of Mazama's summit area and the formation of the Crater Lake caldera, the spectacular geological events were over. However, there are a number of important events which have occurred since the basin was formed. Some of these are volcanic in nature representing the dying phases of Mount Mazama, while others reflect the adjustment to a new topographic feature; the sudden presence of the caldera basin.

Post Collapse Volcanism

Even though the summit disappeared into Mazama's interior, volcanic activity continued for some time. All evidence indicates that post collapse eruptions were confined to the interior of the caldera and that all rocks, now part of the old mountain, resulted from activity prior to collapse. Volcanic eruptions were not extensive and are most likely represented by (1) construction of two cinder cones and (2) lava flows on the caldera floor. It's also possible that a dacite dome was constructed just east of Wizard Island at this time.

6-1 WIZARD ISLAND The base of the Wizard Island cinder cone is surrounded by basal lava flows. Those extending toward the western caldra wall are most prominent and may be easily seen from the Watchman Overlook. They represent the youngest volcanism present in Crater Lake National Park.



6-2 POST COLLAPSE FEATURES Main post caldera volcanic features are located on the floor of Crater Lake and include Merriam Cone and Wizard Island along with possible lava flows. These flows, if present, are thought to be covered by sediments accumulated since their formation.

Lava flows are suspected to have accumulated on the caldera floor, especially near Wizard Island and in the eastern portion of the basin southeast of Merriam Cone (Map 6-2). Near Merriam Cone, the topographic surface of the floor is nearly flat over an area of several square kilometers (square miles). This led to speculation that a lava lake developed here shortly after the summit collapsed. If this flat area represents lava flows, they may be associated with late eruptions of Merriam Cone. Lava that breaks out at the base of a cinder cone, near the end of its active eruption period, is a common occurrence.

Less open to speculation is the region at the western end of the lake. Wizard Island rests on a latform thought to be the accumulation of post-ollapse lava flows. There are two opinions concerning

the emplacement of these flows. A common feature of large calderas is a circular fracture system located just inside the caldera walls. This zone, known as a ring fracture, is usually the site of pyroclastic eruptions and dacite dome emplacement following the cataclysmic collapse of the surface when the caldera was formed. Both Merriam Cone and Wizard Island are located approximately where a ring fracture should exist, if one were present. There was, before the early 1980's, little evidence to suggest the presence of a ring fracture.

A 7,000 year old volcanic feature, such as the Crater Lake caldera, would be expected to show a significant amount of residual heat. Until recently, no evidence of leftover volcanic heat had been found. The great accumulation of cold water had completely masked any such heat reaching the bottom of the lake. In the early 1980's, a team of USGS scientists made a series of heat measurements in bottom sediments. This research located at least two areas with higher than usual temperatures (Map 6-2). These are interpreted as thermal springs which carry hot fluids from as deep as 2 km (1.25 mi) below the lake floor. Moreover, these areas of high heat flow are located close to where a ring fracture would be expected. Thus, it seems there is evidence suggesting that both a ring fracture and continued volcanic heat is present in the Crater Lake caldera.

From the above discussion, the suspected lava flows on the western end of the caldera floor could be associated with a ring fracture which filled it to a depth of nearly 500 m (1600 ft). Conversely, they may be the result of late eruptions issuing from the base of Wizard Island. A casual inspection of Wizard Island indicates that basal flows form part of the island above water level (Picture 6-1). Since the thickness and amount of lava accumulated in the western portion appears to be large, it seems likely that multiple flows occurred. Such a conclusion favors many eruptions from a ring fracture rather than basal flows from Wizard Island. Although the amount of lava flowing from late eruptions of cinder cones can be relatively large, multiple flows are much less frequent.

Other than the construction of Wizard Island, the most obvious post-collapse volcanic event was the eruption of materials to build a cinder cone over 400 m (1,300 ft) high in the northern part of the caldera.

Merriam Cone lies about 1.5 km (1 mi) from the north caldera wall and is about 1.5 km (1 mi) in diameter (Map 6-2). From the depth contours of recent topographic maps, it appears that this cinder cone is unusually symmetrical. The material composing its slopes lies at an angle which indicates eruptions had occurred before any significant amount of water had collected in the caldera. This fact suggests that Merriam Cone was constructed in air shortly after the caldera formed. Samples dredged from the southeast flank of this feature are similar to the volcanic scoria that occurs on the Wizard Island cinder cone.

Wizard Island

Perhaps the most spectacular cinder cone in the world sits along the western shore of Crater Lake; Wizard Island. One story credits William Steel with naming Wizard Island because he thought it was shaped like a Wizard's hat. Certainly, one of its most strikng characteristics is the symmetry of the upper portion of the island. As noted above, Wizard Island represents a cinder cone with associated basal lava flows. Its overall size, with a diameter at the base of about 1,000 m (0.6 mi) and a height of nearly 250 m 800 ft), is somewhat smaller than Merriam Cone. Unlike Merriam Cone, Wizard Island has a well developed summit crater some 125 m (400 ft) across and 25 m (90 ft) deep.

Dating the volcanic activity which constructed Wizard Island, tends to provide more dependable results than is achieved for other post collapse events. The basal flows which make up the western portion of the island support a meager growth of trees (Picture 6-1). Using a dating method which compares tree growth rings, he oldest trees growing here are about 800 years old. ince basal flows tend to occur near the end of a cinder cone's active eruptive life, trees on this flow most likely indicate a minimum time since the last eruption of Wizard Island. In addition, as noted in hapter Two, the life history of a typical cinder cone xtends over only a few tens of years. For Wizard sland, this means the cone and its basal lava flows ould have formed at about the same time. If two hunred years were allowed for the trees to establish hemselves on this rather barren terrain, an age of pproximately 1,000 years can be assigned. Other obserations, such as the fresh appearance of the lava and yroclastic material, also tend to confirm the youthulness of Wizard Island.

The lava flow extending westward from the base of Wizard Island is thought to represent the last major volcanic activity in Crater Lake National Park. Outside the caldera there are no hot areas to suggest remnant volcanism. Features such as fumaroles, mudpots, steam vents or other signs which indicate magma still exists below the caldera, have never been observed. However, as noted above, recent evidence from heat flow measurements on the lake floor do suggest a source of heat still exists below. The most likely interpretion of these new findings is residual heat from cooling magma. In somewhat the same category are the circular "holes" which have been reported in Fumarole Bay along the southwest side of Wizard Island (Map 6-2). These were originally reported as fumaroles formed prior to the lake level reaching its current height. Recently, this interpretation has been questioned and an alternative explanation suggests the depressions are tree casts resulting from a lava flow which trapped trees in an upright position. At this time, there is no consensus of which of these ideas, or some new interpretation, is most likely correct.

One other unusual feature just east of Wizard Island has been identified. Its appearance on the depth contour map of Crater Lake's floor provides little evidence of what this structure is or how it formed. Based on dredged samples of dacite, the favored interpretation suggests that an intruded dome is located here (Map 6-2). Dacite domes are common features associated with ring fractures in larger calders. The feature in question appears to be too far from the caldera wall to be associated with a potential ring fracture but may be an isolated dacite dome emplaced by late eruptive activity.

Sedimentation in Crater Lake

Until about 1960 little attention had been directed toward the possibility of sedimentation on the caldera floor. The prevailing concept viewed the entire floor topography as resulting from volcanic activity. In addition, with the age of the caldera placed at less than 7,000 years, there didn't seem to be enough time for any significant thickness of sediments to accumulate. Recently, geophysical and bottom sampling work indicates that a sediment layer does exist over much of the lake floor. The favored interpretation is based on deposition resulting from turbidity currents.

Turbidity currents are generated by slumping of ose materials resting on a steep slope. At Crater ke the loose debris remaining from the collapse of zama's summit could form such a slope along the in- de of the caldera. Indeed, much of the existing wall posed above lake level displays loose material and riodically a debris slide can be seen. This process uld likely have been rather common for some time rectly following the collapse. When such a slide curs, it mixes with water to form a current which is avier than lake water. As a consequence it flows in a annel until its energy is used up and then slowly ttles out in a layer on the level portion of the lake ttom. Although there is no way of knowing how often rbidity currents occurred or how many may have de- sited sediments on the caldera floor, they were like- frequent events, numbering in the hundreds.

If this interpretation is correct, it has impor- nt implications on earlier concepts of the nature of ater Lake's floor. As an example, the flat area (Map 4) representing the deepest part of the lake, could the result of sediments deposited from turbidity rrents rather than lava flows from Merriam Cone. Of urse, it may be a combination of these two processes th sediments covering the original lava flows. Also, y evidence that may have been preserved on the ldera floor, that would indicate how the callapse curred, would now be buried below many feet of sedi- nt. From work completed so far, the presence of sign- icant sediment layers has been verified in the three ke bottom basins.

ing of Crater Lake

The current lake level and its constant surface evation appear to have developed from precipitation er the 71 square kilometers (27.5 sq mi) of surface ainage. Evaporation and seepage together remove ough water to balance the incoming precipitation. en though the filling of the Crater Lake caldera is e of the most recent events to occur in the park, the ocess is largely a matter of speculation based on a w observations and facts. Most of the facts have been own for years and include details such as water temp- ature, depth, volume and surface area, average pre- pitation, and topographic configuration of both the ke floor and land surface. Speculation is centered on lculations which estimate evaporation from the lake face and percolation into porous zones in the bottom l sides of the basin.

6-3 LAKE GAUGING STATION This automatic lake level recording device is the most recent of many attempts to measure fluctuations of Crater Lake. The earliest method consisted of a simple reference "pin" hammered into a rock located at lake level below Sinnott Memorial Overlook.

6-4 ANNIE SPRINGS One of the largest of the many springs which occur on the south flank, can be seen just inside the entrance station. Evidence indicates its source of water is rain and snow runoff rather than seepage from Crater Lake.

As Williams clearly stated, there does not seem to be any way of determining what time span was required for the caldera to be filled to its present level. Calculations based on climatic conditions, like those now observed, suggest filling would require a minimum time of between 700 and 1,500 years. There are simply too many unknown factors to allow a more accurate prediction. On the other hand, there is no strong evidence, such as higher beach lines, to indicate that lake level was significantly higher than the current position. Although there have been fluctuations, with a range of as much as twenty-two feet, between the lowest to highest level recorded, the yearly variation amounts to only three or four feet. In summary, a common explanation is that water accumulated from precipitation until it gradually reached the present level. With the lake at its present elevation, the amount of surface area pro-

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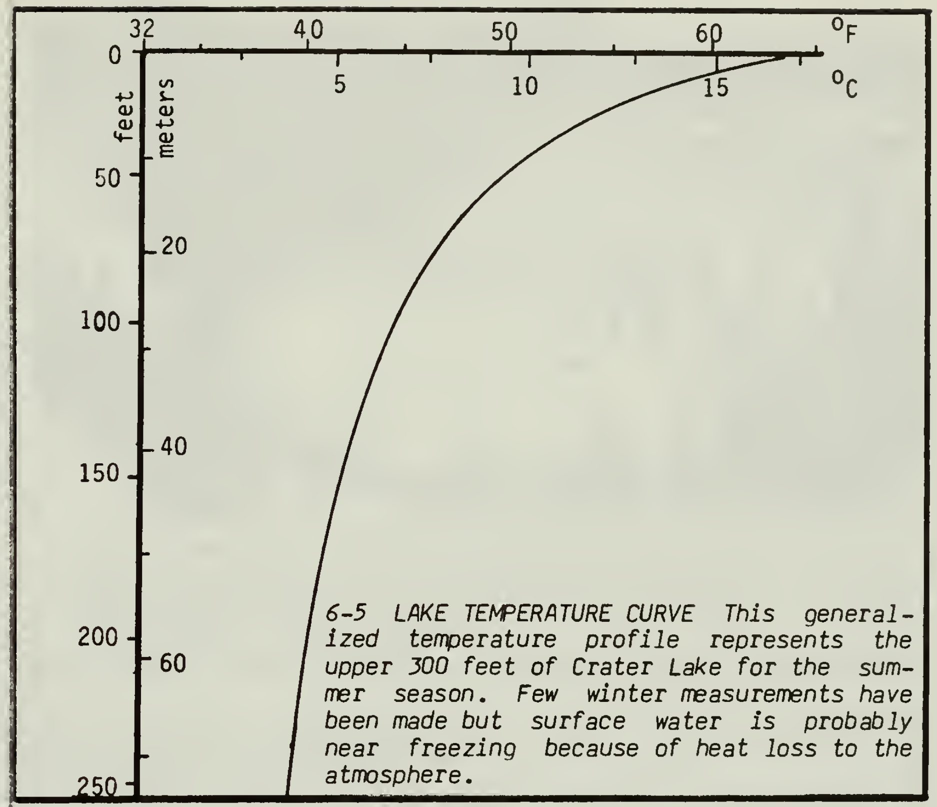
iding evaporation and the porous zones encountered elow lake level just offset the incoming precipitation. From lake level measurements made over nearly inety years, the lake appears to have reached an quilibrium: water added is balanced with that removed Picture 6-3).

Early investigators set up a number of experiments esigned to establish the relationship between how ater is added and removed from Crater Lake. These were argely concerned with evaporation from the lake's surace and consideration of how water might escape by ercolation. Evaporation measurements suggest about wo-thirds to three-fourths of the water is lost by vaporation and the balance by seepage through porous ock layers. Numerous springs on the outer flanks of ount Mazama may represent escaping lake water, but ith one exception, no connection has been demonstrated Picture 6-4). Recent chemical evidence from a large pring that marks the beginning of the Wood River, bout 20 km (12 mi) to the southeast, indicates the ater is from Crater Lake. With this tentative exception, the story of how Crater Lake collected in the aldera basin has changed little since the 1890's.

ater Lake's Water

Perhaps the single most unusual feature of Crater ake National Park is the color of the water. Visitors, on first seeing the lake, can frequently be overheard arvelling at the deep blue color, just as the members the Hillman party did over 125 years ago. Although s color may vary over a wide range of shades, the ep indigo is the most dramatic. The explanation seems be related to a number of factors including water pth, transparency, purity, steepness of the caldera lls, and others. One probable cause is based on the ture of water molecules and their ability to scatter ght. As a result of this scattering, the blue portion the original sunlight entering the water is concen-ated back toward the surface.

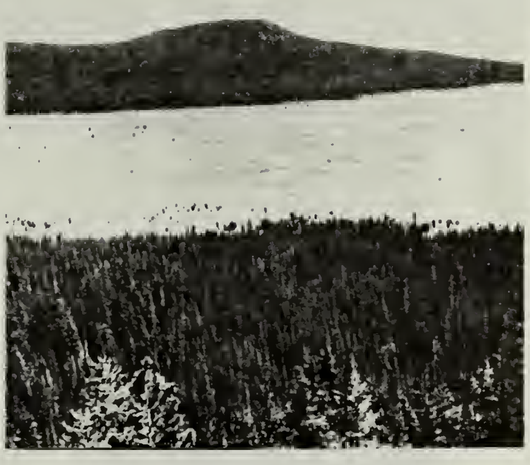
Almost as unusual as its color is the purity of ater Lake water. As one researcher noted, it is ntermediate between dust-free and distilled water." deed, eighty percent of all its water is distilled ter in the form of snow or rain falling directly into e lake. An additional sixteen percent is snowfall or in that rapidly reaches the lake from the surounding sin walls. Chemical analysis reports most elements or mpounds in a few parts per million, extremely low for surface water. Moreover, the amount of suspended solid matter is also very low. Taken together, these two characteristics make Crater Lake water some of the most distinctive found anywhere in nature. One interesting aspect of this purity is the transparency of the water and the depth to which light will penetrate. Measurements over the years have consistently indicated visibility to depths well over 100 m (325 ft) and measurable amounts of light on the bottom have even been recorded.



6-5 LAKE TEMPERATURE CURVE This generalized temperature profile represents the upper 300 feet of Crater Lake for the summer season. Few winter measurements have been made but surface water is probably near freezing because of heat loss to the atmosphere.

As might be expected, based on the source of the lake's water and its elevation, Crater Lake is cold. A typical summer temperature profile is shown in figure 6-5. A maximum temperature of about 18° C (65° F) is reached in late summer at the surface. It then decreases with depth down to about 100 m (325 ft) where it stabilizes at 4° C (39° F). During winter months, surface heat is lost to the cold air until a near freezing temperature is achieved. However, only rarely, has Crater Lake completely frozen over. This unsuspect-

6-6 LLAO'S HALLWAY Rapid erosion by runoff water has cut deeply into the final eruption ash. This side canyon of Castle Creek represents an early stage while many of the major valleys have enlarged to display flat floors with steep walls (Picture 6-8).

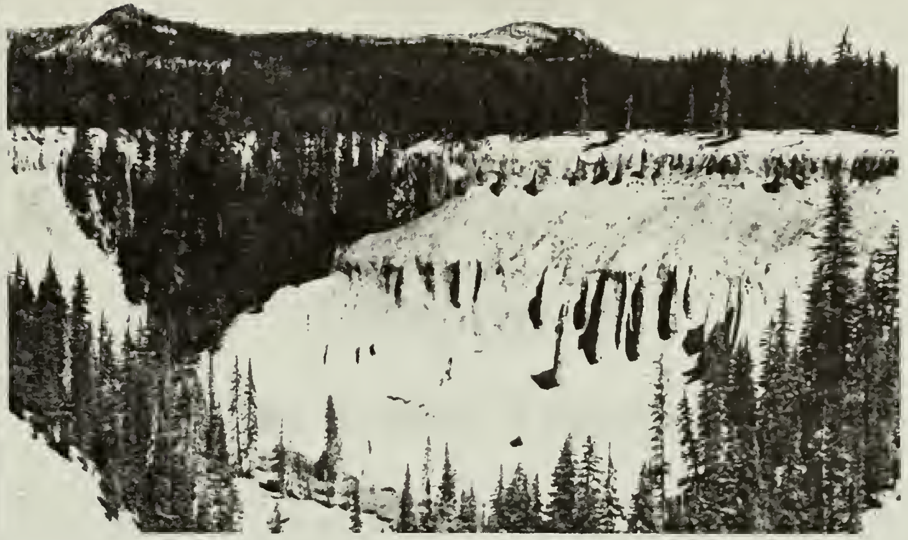


6-7 PUMICE DESERT Several hundred feet of ash flow material was deposited north of Mount Mazama during the final eruption. Low water content and high surface temperatures in the summer contribute to the harsh conditions making plant growth difficult.

ed condition results from several factors including surface currents driven by the strong winter winds and its great depth.

Post Collapse Erosion

As noted in Chapter Four, running water is an important agent of erosion and is undoubtedly the major cause of erosion outside the caldera since the collapse. Even a casual inspection of the streams flowing down Mazama's slopes today will verify this conclusion (Picture 6-6). As the climactic ash flows poured down the pre-collapse stream valleys, their original shapes were covered with as much as several hundred feet of pyroclastic material (Picture 6-7). With the reestablishment of streams in these ash flows, rapid erosion by running water quickly cut down into the loose ash (Picture 6-8). The result of nearly seven thousand years of erosion can readily be seen along



6-8 GODFRY GLEN As Annie Creek cut down through the ash flows this large, flat floored valley was formed. The far wall illustrates pinnacle-like structures similar to those in Sand Creek Canyon (Cover).

park roads boardering Annie Creek, The Pinnacles, and Castle Creek (Appendix Map).

Crater Lake, as we find it today, is the result of not only its long volcanic history of mountain building and caldera formation, but also the climatic conditions of the last few thousand years. The 15 m (50 ft) of annual snowfall has played a major role in creating the Crater Lake scenery. Following the collapse, high precipitation has both filled the caldera and sculptured the surrounding topography. Is this the conclusion of the Crater Lake story or will there be another more exciting chapter written by future geological events? Chapter Seven looks at this question.

Chapter 7

Crater Lake Tomorrow

As any visitor can readily determine, both Crater Lake and Crater Lake National Park exist because of geological events that have transpired over the last several thousand years in central Oregon. Like many other national parks, Crater Lake was established to protect and preserve the geological setting and other natural aspects of this area. This commitment by the people of the United States through Congress ensures that future visitors will find the park, and its geology, in a natural state just as it is today. Does this mean that nothing will change? On the contrary. Natural systems are dynamic and include geological changes, which although slow as man reckons time, continue to operate at Crater Lake.

Volcanic activity along the Cascades has not been pronounced over the last two hundred years; the period since the region has been densely populated. From a human perspective, this quiet period may be considered typical. However, episodes of much greater volcanism are every bit as typical for these volcanoes. Will Crater Lake share in any renewed activity along this volcanic mountain chain? Geologists find questions

7-1 MOUNT THIELSEN In contrast to the younger High Cascade volcanoes, Mount Thielsen, a few miles north of Crater Lake, is an example of an older series of volcanoes. Union Peak, in the southern part of the park, also belongs to this previous period of activity and both show extensive erosion since they last erupted, perhaps over 100,000 years ago.

7-2 BUMPASS HELL This hot spring, venting sulfur-rich water and steam in a small valley in Lassen Volcanic National Park, is associated with subsurface volcanism. Hydrothermal features and fumaroles are direct evidence of hot rocks below the surface. These are common in the Cascades, but at Crater Lake none are present, except those on the lake floor.

like this some of the most difficult to answer. Predicting future geological events, especially volcanic ctivity and earthquakes, has only recently become an rea of systematic study. Although no detailed forecasts can be made concerning the geological future of rater Lake, some suggestions are possible.

As noted in Chapter Six, the only known hot areas n the park occur on the caldera floor masked by the old lake water. However, a survey of other areas in he Cascades finds many locations with hot springs, oiling mud pots, fumaroles and other direct indications of volcanic heat beneath the surface. Excellent xamples of such features can be found at Lassen Vol- anic National Park in northern California (Picture -2). These areas most likely represent near-surface agma bodies. Recent drilling near Mount Hood and in ewberry Crater has also found water at unusually high emperatures. This has lead to a new concept which sug- ests that much of the Cascade Range is underlain by eat sources; magma bodies, which are masked by the uch cooler water near the surface.

Since the time when pioneers and settlers populated the Pacific Northwest, about half the Cascade volcanoes have been observed in eruption. Magma bodies have reached the surface at these locations. Between 1914 and 1921 explosive activity and a lava flow occurred at Lassen's crater. Even more familiar are the recent eruptions of Mount St. Helens in southern Washington. In general, many Cascade volcanoes, that have been observed in eruption, also tend to display hydrothermal features like those at Lassen. With the discovery of thermal springs on the floor of Crater Lake, some kind of heat source is suggested below old Mount Mazama. As we have seen in Chapter Four, the site now occupied by Crater Lake has been the focus of volcanism for many hundreds of thousands of years. It is not unreasonable to expect similar activity to continue in the future.

If renewed eruptions were to occur, where would they most likely develop and what might be expected? Again, an educated guess can be made based on the geological history observed in other calderas. Older, and larger calderas commonly exhibit a ring fracture system as discussed in Chapter Six. This zone of weakness develops just inside the caldera walls and appears to connect the magma chamber with the surface, providing an avenue for liquid rock, gases, and hydrothermal fluids to escape upward. If such a structure exists at Crater Lake, any renewed volcanism would likely be associated with this zone (Map 6-2). Eruptions would therefore occur on the lake bottom near the margins of the caldera. Cinder cones and dacite domes would be the most likely features formed, depending on the kind of magma present in the underlying chamber. These are typical features produced in other calderas. Due to its youthfulness and location, Wizard Island is often suggested as a prime candidate for the next episode of volcanism. However, cinder cone history dictates otherwise. Unless it's atypical, Wizard Island's period of eruption is past. It's a dead volcano!

These sketchy predictions could be considered as near future possibilities in a geological time framework. Prospects for long-term activity are even less sure and depend on many factors, some of which are completely unknown at this time. The entire Cascade Range may be waning if the cause lies with the subduction zone described in Chapter Three. If the ocean floor ceases to slide beneath the continental margin, the energy source and origin of magma will also diminish, eventually stopping altogether. Lack of earth-

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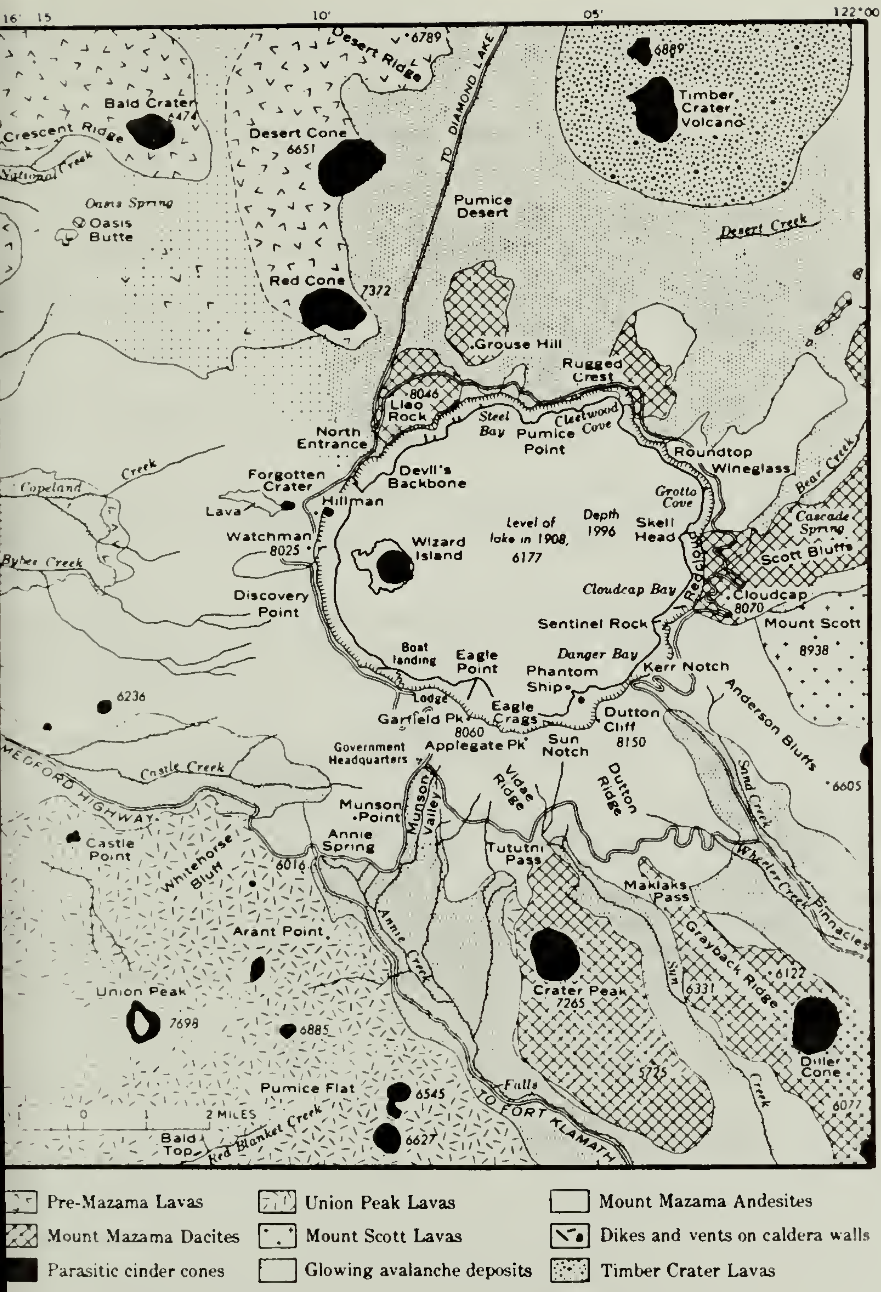
quakes below the Cascades may indicate that there is slow movement or no movement at all along this subduction zone. This would make sense as most of the ocean floor plate has been consumed, and according to theory, subduction should end. However, the behavior of this subduction zone is not well understood and this interpretation may be completely wrong. Perhaps movement is sporadic and the present time is simply a quiet period, as some research seems to indicate. Although arguments can be made for either situation, the final decision waits on time; geological time.

Appendix



Generalized geologic map of Crater Lake and Vicinity. Plate 3. Carnegie Inst of Washington Pub No. 540. 1942

References

Alt, D.D. & Hyndman, D.W., 1978, ROADSIDE GEOLOGY OF OREGON, Mountain Press Publishing Co., 268 pgs.

Bacon, C.R., & Charles 1981, Personnal Communication US Geological Survey, Geolog Divisi Menlo Park, c

Chapin, C.E. & Elston, W.E., Editors, 1979, ASH FLOW TUFFS, Special Paper 180, The Geological Society of America, 211 pgs.

Clark. E.E., 1953, INDIAN LEGENDS OF THE PACIFIC NORTHWEST, University of California Press, 225 pgs.

Diller, J.S. & Patton, H.B., 1902, THE GEOLOGY AND PETROLOGRAPHY OF CRATER LAKE NATIONAL PARK, U.S.G.S. Professional Paper 3, 167 pgs.

Frances, P., 1976, VOLCANOES, Pelican Books, 386 pgs.

Harris, S.L., 1976, FIRE AND ICE - THE CASCADE VOLCANOES, The Mountaineers - The Pacific Search Press, 320 pgs.

Kettleman, L.R., 1973, Mineralogy, Correlation, and Grain-Size Distribution of Mazama Tephra and other Post Glacial Pyroclastic Layers, Pacific Northwest, GEOLOGICAL SOCIETY OF AMERICAN BULLETIN, vol. 84, pgs 2957-2980.

_______________, 1979, Tephra, SCIENTIFIC AMERICAN, vol. 24, no. 6 (Dec.), pgs 160-170.

Lidstrom, J.W. Jr., 1972, A NEW MODEL FOR THE FORMATION OF CRATER LAKE CALDERA, OREGON, unpublished PhD thesis, Oregon State University, 85 pgs.

McKee, B., 1972, CASCADIA, THE GEOLOGIC EVOLUTION OF THE PACIFIC NORTHWEST, McGraw-Hill Book Co., 394 pgs.

Mehringer, P.J. Jr., Blinman, E. & Peterson, K.L., 1977, Pollen Influx and Volcanic Ash, SCIENCE, vol. 198, pgs. 257-261.

Nelson, C.H., 1961, GEOLOGICAL LIMNOLOGY OF CRATER LAKE, OREGON, unpublished MS thesis, University of Minnesota, 175 pgs.

Richey, J.L., 1979, ORIGIN OF DIVERGENT MAGMAS AT CRATER LAKE, OREGON, unpublished PhD thesis, University of Oregon, 209 pgs.

Rittman, A., 1962, VOLCANOES AND THEIR ACTIVITY, Interscience Publications, 305 pgs.

Seyfert, C.K. & Sirkin, L.A., 1973, EARTH HISTORY AND PLATE TECTONICS, Harper & Row, 504 pgs.

Sparks, R.J., Siguardsson, H. & Wilson, L., 1977, Magma Mixing: A Mechanism for Triggering Acid Explosive Eruptions, NATURE, vol. 267, pgs. 315-318.

United States Geological Survey (USGS), 1956, CRATER LAKE NATIONAL PARK AND VICINITY (topographic map).

Williams, D.L. & Von Herzen, R.P., 1982, On the Terrestrial Heat Flow and Physical Limnology of Crater Lake, Oregon, JOURNAL OF GEOPHYSICAL RESEARCH, in press.

Williams, H., 1942, THE GEOLOGY OF CRATER LAKE NATIONAL PARK, OREGON, Carnegie Institute of Washington Publication 540, 162 pgs.

, 1954, CRATER LAKE, THE STORY OF ITS ORIGIN, University of California Press, 98 pgs.

, 1961, The floor of Crater Lake, Oregon, AMERICAN JOURNAL OF SCIENCE, vol. 259, pgs. 81-83.

, & Goles, G., 1968, Volume of the Mazama Ash-Fall and the Origin of Crater Lake, Oregon, in ANDESITE CONFERENCE GUIDEBOOK (A.R. McBirney, Ed.), Oregon Department of Geology & Mineral Industries Bulletin 62, pgs. 37-41.

, & McBirney, A.R., 1979, VOLCANOLOGY, Freeman, Cooper & Co., 397 pgs.

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About The Author

Rod Cranson has served as a ranger at Crater Lake National Park for seven seasons over the past fifteen years. During this period, and even before, he has studied the geology of this classic area. Volcanoes and volcanology have been a fascination for him since early in his college studies. In addition to travel in the Pacific Northwest, Rod has visited many volcanic areas in other parts of the United States, Canada and Mexico.

He received both his Bachelors of Science and Masters degrees from Michigan State University in preparation for a career in petroleum geology. However, the opportunity to teach geology in high school led to a career in education. This allowed summer tours of many western National Parks which strengthened his interest in these natural treasures. They have become an important part of his geological education.

Rod has taught undergraduate geology and natural science at Lansing Community College, Michigan, for over sixteen years. The last several years have combined teaching with graduate studies in geology including research at Crater Lake. Sharing his interests in geology, mountaineering, photography and writing are his wife, Sharon, and children, Keri and Kurt.